

Interim Pilot Study Report



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Prepared by



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Contents

Executive Summary.....	ES-1
Summary of Testing.....	ES-3
Coagulant Selection.....	ES-3
Pre-ozonation.....	ES-4
Prechlorination.....	ES-4
Filter Performance.....	ES-5
Chapter 1. Introduction.....	1-1
1.1 Document Structure.....	1-1
1.2 Background.....	1-2
1.3 Pilot Plant Study Objectives.....	1-2
1.4 Water Treatment Goals.....	1-3
1.5 Test Plan.....	1-5
1.5.1 Summary of Testing Through October 2019.....	1-5
1.5.2 Summary of Testing Planned Through June 2020.....	1-7
Chapter 2. Pilot Plant Configuration.....	2-1
2.1 Flocculation and Sedimentation Pilot Unit.....	2-3
2.2 Ozonation Pilot Unit.....	2-4
2.3 Filtration Pilot Unit.....	2-5
2.3.1 Filter Media Configuration.....	2-6
2.3.2 Filter Backwash Setpoints.....	2-7
2.4 Discharge and Solids Handling.....	2-7
2.5 Varying Operational Parameters.....	2-8
2.6 Water Quality Data Collection.....	2-10
2.6.1 Comprehensive Water Quality Sampling.....	2-10
2.6.2 Sampling Locations.....	2-11
2.6.3 Online Instrumentation.....	2-12
2.6.3.1 Turbidimeters.....	2-12
2.6.3.2 Particle Counters.....	2-12
2.6.3.3 pH Probes.....	2-12
2.7 Discharge Compliance and Mitigation of Risk to Aquatic Life.....	2-12
Chapter 3. Raw Water Characteristics.....	3-1
3.1 Raw Water Turbidity.....	3-5
3.2 Algae Levels in Raw Water.....	3-6
3.3 Floc Sed Inlet Particle Counts.....	3-7
3.4 Summary.....	3-9
Chapter 4. Pilot Study Results.....	4-1
4.1 Filter Operation.....	4-1
4.1.1 Analysis Parameters.....	4-1
4.1.1.1 UFRVs.....	4-2

4.1.1.2	Particle Counts	4-4
4.1.1.3	Organics Removal	4-5
4.2	Coagulant Testing and Selection	4-5
4.2.1	Bench-scale Jar Testing	4-6
4.2.2	Pilot Coagulant Selection–Summer/Fall Season	4-7
4.2.2.1	Alum – Initial Screening	4-8
4.2.2.2	Ferric Chloride	4-12
4.2.2.3	PACI – Initial Screening	4-14
4.2.2.4	ACH 7	4-17
4.2.2.5	Alum vs. PACI Side-by-side Comparison	4-21
	Filtration Rates of 6 and 8 gpm/sf	4-22
	Filtration Rates of 8 and 12 gpm/sf	4-25
	Without Filter Aid	4-27
	Additional Testing with Filter Aid	4-32
	Evaluation of Coagulant Performance with Pre-oxidation	4-35
	Organics Removal for Side-by-Side Comparison	4-38
4.2.3	Summary of Pilot Coagulant Comparison–Summer/Fall Season	4-42
4.3	Pre-oxidant Testing	4-42
4.3.1	Ozone Kinetics	4-42
4.3.1.1	Bench-scale Testing	4-42
4.3.1.2	Pilot-scale Ozone Demand and Decay	4-43
4.3.2	Pre-ozonation vs No pre-oxidation	4-46
4.3.2.1	Summary	4-57
4.3.3	Pre-chlorination vs Pre-ozonation	4-58
4.3.3.1	Summary	4-69
4.4	Direct Filtration Testing	4-70
4.5	Settled Water Quality	4-71
4.6	Summary	4-73
Chapter 5.	Filter Performance Comparison	5-1
5.1	Clean Bed Head Loss	5-1
5.2	Turbidity	5-3
5.3	UFRVs	5-5
5.4	Organics Removal	5-6
5.4.1	Filtration Rate Comparison	5-7
5.4.2	Filter Media Comparison	5-9
5.5	Biological Activity Monitoring	5-12
5.5.1	ATP (Liquid and Media)	5-12
5.5.2	AOC Removal	5-14
5.6	Summary	5-17
Chapter 6.	Chlorine Demand/Decay and DBP Testing	6-1
Chapter 7.	Summary of Interim Pilot Plant Results	7-1
References.	R-1

Appendix A: Jar Testing Report(s).....	A-1
Appendix B: Bench-Scale Ozone Demand-Decay Testing Report.....	B-1
Appendix C: Appendix C: Simulated Distribution System and Disinfection Evaluation.....	C-1

List of Figures

Figure 1-1. Summary of Pilot Testing from February through October 2019.....	1-6
Figure 2-1. PWB pilot plant dual train process flow diagram	2-2
Figure 2-2. Intuitech flocculation-sedimentation module 1000 (model S300) at the pilot plant.....	2-3
Figure 2-3. Intuitech ozonation module (model Z300) at the pilot plant	2-4
Figure 2-4. Intuitech 6-column filtration module, model F300 at the pilot plant	2-5
Figure 2-5. Rain For Rent settling basin tank at the pilot plant	2-8
Figure 3-1. Influent temperature from July 1–October 31	3-2
Figure 3-2. Influent alkalinity (left axis) and pH (right axis) from July 1–October 31	3-4
Figure 3-3. Influent TOC (left axis) and filtered UV ₂₅₄ (right axis) from July 1–October 31.	3-4
Figure 3-4. Raw water turbidity levels in the pilot trains from July 1 – October 31	3-5
Figure 3-5. Total algal density in the intake from July 31–October 31	3-6
Figure 3-6. Algal density for the five genera with the maximum densities sampled from July 1 to October 31	3-7
Figure 3-7. Particle counts at the Floc Sed 1000 inlet (Train 1) intake from July 31–October 31	3-8
Figure 4-1. Pilot filter arrangement showing the train, filter number, media, depth, and filtration rate.....	4-2
Figure 4-2. Example of data used when calculating filter run time	4-4
Figure 4-3. Comparison of Filter 6 turbidity data (top) to Filter 6 turbidity data corresponding to calculated filter run times (bottom) during initial alum screening.....	4-9
Figure 4-4. Calculated UFRVs during the initial screening of alum on Train 1 from July 1 - 8.....	4-10
Figure 4-5. Filter effluent turbidities recorded during accepted filter runs during the initial screening of alum on Train 1 from July 1 - 8	4-11
Figure 4-6. Overall organics removal performance during the initial screening of alum (July 1-8)	4-12
Figure 4-7. Turbidity data from Filter 3 during the initial ferric coagulant screening	4-13
Figure 4-8. Overall organics removal performance during the initial ferric coagulant screening, July 9 - 15	4-14
Figure 4-9. Calculated UFRVs during the initial screening of PACl on Train 1 from July 9 - July 15.....	4-15
Figure 4-10. Filter effluent turbidities recorded during accepted filter runs during the initial screening of PACl on Train 1 from July 9 - July 15	4-16
Figure 4-11. Overall organics removal performance with PACl during the initial screening of PACl, July 9 - 15	4-17
Figure 4-12. Turbidity data from Filter 3 during the initial ACH coagulant screening	4-18
Figure 4-13. Calculated UFRVs during the initial screening of ACH on Train 2 from July 1 – 8	4-19
Figure 4-14. Filter effluent turbidities recorded during accepted filter runs during the initial screening of ACH on Train 2 from July 1 – 8.....	4-20
Figure 4-15. Overall organics removal performance during the initial screening of ACH, July 1-8	4-21
Figure 4-16. Calculated UFRVs during the side-by-side testing of alum and PACl at 6 and 8 gpm/sf, conducted from July 15 –26.....	4-23

Figure 4-17. Filter effluent turbidities recorded during accepted filter runs during the side-by-side testing of alum and PACl at 6 and 8 gpm/sf, conducted from July 15 –26.....	4-24
Figure 4-18. Filter effluent turbidity over time from Filter 1 during accepted filter runs during the side-by-side testing of alum and PACl at 6 and 8 gpm/sf, conducted from July 15 –26.....	4-25
Figure 4-19. Calculated UFRVs during the side-by-side testing of alum and PACl at filtration rates of 8 and 12 gpm/sf, conducted from July 26 –30	4-26
Figure 4-20. Filter effluent turbidities recorded during accepted filter runs during the side-by-side testing of alum and PACl at filtration rates of 8 and 12 gpm/sf, conducted from July 26 –30.....	4-27
Figure 4-21. Calculated UFRVs during side-by-side testing of alum and PACl with no filter aid, from July 30 – August 5	4-28
Figure 4-22. Filter effluent turbidities recorded during accepted filter runs during the side-by-side testing of alum and PACl with no filter aid, from July 30 – August 5	4-29
Figure 4-23. Calculated UFRVs during side-by-side testing of alum and PACl with filter aid, from August 5 –12	4-32
Figure 4-24. Filter effluent turbidities recorded during accepted filter runs during the side-by-side testing of alum and PACl with filter aid, from August 5 –12	4-33
Figure 4-25. Calculated UFRVs during side-by-side testing of alum and PACl following ozone pre-oxidation, conducted August 20 –30	4-35
Figure 4-26. Filter effluent turbidities recorded during accepted filter runs during side-by-side testing of alum and PACl following ozone pre-oxidation, conducted August 20 – 30	4-36
Figure 4-27. Organics removal for Filters 1 and 6—alum vs PACl: TOC	4-39
Figure 4-28. Organics removal for Filters 3 and 4—alum vs PACl: TOC	4-39
Figure 4-29. Organics removal for Filters 1 and 6 —alum vs PACl: filtered UV ₂₅₄	4-40
Figure 4-30. Organics removal for Filters 3 and 4 —alum vs PACl: filtered UV ₂₅₄	4-40
Figure 4-31. Organics removal for Filters 1 and 6—alum vs PACl: Apparent color	4-41
Figure 4-32. Organics removal for Filters 3 and 4—alum vs PACl: Apparent color	4-41
Figure 4-33. Ozone residual over time.....	4-43
Figure 4-34. Pilot-scale ozone residual curve for Train 1 and Train 2, Ozone Dose of 1 mg/L (T1).....	4-44
Figure 4-35. Boxplot of ozone residual curve for Train 2, Ozone Dose of 1 mg/L (T2).....	4-45
Figure 4-36. Treatment train for pre-ozonation treatment evaluation.....	4-46
Figure 4-37. Calculated UFRVs during side-by-side testing of pre-oxidation vs. no pre-oxidation, conducted August 30 – September 30	4-47
Figure 4-38. Filter effluent turbidities recorded during accepted filter runs during side-by-side testing of pre-oxidation vs. no pre-oxidation, conducted August 30 – September 30	4-48
Figure 4-39. Comparison of particle counts from 72-inch anthracite filters treating water that has been pre-oxidated with ozone (Filter 1, top) vs. water that has not been pre-oxidated (Filter 6, bottom).....	4-50
Figure 4-40. Organics Removal for Filters 1 and 6 - pre-ozonation vs no pre-oxidation: TOC	4-51
Figure 4-41. Organics Removal for Filters 3 and 4 - pre-ozonation vs no pre-oxidation: TOC	4-52
Figure 4-42. Organics Removal for Filters 1 and 6 - pre-ozonation vs no pre-oxidation: filtered UV ₂₅₄	4-52

Figure 4-43. Organics Removal for Filters 3 and 4 - pre-ozonation vs no pre-oxidation: filtered UV ₂₅₄	4-53
Figure 4-44. Organics Removal for Filters 1 and 6 - pre-ozonation vs no pre-oxidation: true color	4-53
Figure 4-45. Organics Removal for Filters 3 and 4 - pre-ozonation vs no pre-oxidation: true color	4-54
Figure 4-46. Average TOC by location during comparison of pre-ozonation (Train 2) vs. no pre-oxidation (Train 1) from August 30 to September 29	4-55
Figure 4-47. Average Filtered UV ₂₅₄ by location during comparison of pre-ozonation (Train 2) vs. no pre-oxidation (Train 1) from August 30 to September 29	4-56
Figure 4-48. Average true color by location during comparison of pre-ozonation (Train 2) vs. no pre-oxidation (Train 1) from August 30 to September 29	4-57
Figure 4-49. Treatment train for pre-chlorination vs. pre-ozonation	4-58
Figure 4-50. Calculated UFRVs during side-by-side testing of ozone vs. chlorine pre-oxidation, conducted October 14 – 18	4-59
Figure 4-51. Filter effluent turbidities recorded during accepted filter runs during side-by-side testing of ozone vs. chlorine pre-oxidation, conducted October 14 – 18	4-60
Figure 4-52. Organics Removal for Filters 1 and 6 - pre-chlorination vs no pre-ozonation: TOC	4-62
Figure 4-53. Organics Removal for Filters 3 and 4 - pre-chlorination vs no pre-ozonation: TOC	4-63
Figure 4-54. Organics Removal for Filters 1 and 6 - pre-chlorination vs no pre-ozonation: Filtered UV ₂₅₄	4-63
Figure 4-55. Organics Removal for Filters 3 and 4 - pre-chlorination vs no pre-ozonation: Filtered UV ₂₅₄	4-64
Figure 4-56. Organics Removal for Filters 1 and 6 - pre-chlorination vs no pre-ozonation: True color	4-64
Figure 4-57. Organics Removal for Filters 3 and 4 - pre-chlorination vs no pre-ozonation: True Color	4-65
Figure 4-58. Average TOC by location during comparison of pre-chlorination (Train 1) vs pre-ozonation (Train 2) from October 14 - 18	4-67
Figure 4-59. Average Filtered UV ₂₅₄ by location during comparison of pre-ozonation (Train 2) vs. pre-chlorination (Train 1) from October 14 - 18	4-68
Figure 4-60. Average Color by location during comparison of pre-chlorination (Train 1) vs. pre-ozonation (Train 2) from October 14 - 18	4-69
Figure 4-61. Treatment train for direct filtration treatment evaluation	4-70
Figure 4-62. Turbidity values from Filter 4 (Train 1) during the direct filtration trial, from October 1 - October 11	4-71
Figure 4-63. Comparison of settled and raw water turbidity in Train 1 and Train 2 from July 31 - Oct 31	4-72
Figure 4-64. Settled water particle counts from July 31 to October 31	4-73
Figure 5-1. Clean bed head loss throughout the testing period for acceptable filter runs from July 1 - October 31	5-3
Figure 5-2. Turbidity for all filters from July 26 - October 18	5-4
Figure 5-3. UFRV for all filters from July 26 - October 18	5-6
Figure 5-4. Organics removal for GAC filters (Filter 2 and Filter 3) - filtration rate comparison: TOC	5-7

Figure 5-5. Organics removal for anthracite filters (Filter 5 and Filter 6) - filtration rate comparison: TOC.....	5-8
Figure 5-6. Organics removal for GAC filters (Filter 2 and Filter 3) - filtration rate comparison: Filtered UV ₂₅₄	5-8
Figure 5-7. Organics removal for anthracite filters (Filter 5 and Filter 6) - filtration rate comparison: Filtered UV ₂₅₄	5-9
Figure 5-8. Organics removal for Filter 1 (Anth) and Filter 3 (GAC) – filter media comparison: TOC.....	5-10
Figure 5-9. Organics removal for Filter 4 (GAC) and Filter 6 (Anth) – filter media comparison: TOC.....	5-10
Figure 5-10. Organics removal for Filter 1 (Anth) and Filter 3 (GAC) – filter media comparison: Filtered UV ₂₅₄	5-11
Figure 5-11. Organics removal for Filter 4 (GAC) and Filter 6 (Anth) – filter media comparison: Filtered UV ₂₅₄	5-11
Figure 5-12. Filter media ATP sampling results-September 4.....	5-13
Figure 5-13. Aqueous ATP sampling results.....	5-14
Figure 5-14. Forms of natural organic matter	5-15
Figure 5-15. AOC data from each sampling point.....	5-16
Figure 5-16. Statistical summary of AOC data	5-17
Figure 6-1. SDS test results for 14-day TTHMs and HAA5s	6-3
Figure 6-2. SDS test results for chlorine demand and decay	6-3

List of Tables

Table ES-1. Pilot Study Water Quality Goals and Performance Benchmarks	ES-2
Table ES-2. Summary of testing scenarios for pilot plant study from July 1 to October 31	ES-3
Table ES-3. Pilot-scale Ozone Decay Kinetics ^(a)	ES-4
Table 1-1. Pilot Study Water Quality Goals and Performance Benchmarks	1-4
Table 2-1. Six-Filter Configuration	2-1
Table 2-2. Filter Media Profile Values	2-6
Table 2-3. Current Backwash Initiation Criteria and Operation	2-7
Table 2-4. Pilot Plant Unit Process Variables from July to October 2019 of Operations	2-9
Table 2-5. Comprehensive Water Quality Parameters and Frequency	2-11
Table 3-1. Monthly Average Pilot Raw Water Quality (July 1 to October 31)	3-3
Table 4-1. Summary of testing scenarios for pilot plant study from July 1 to October 31	4-1
Table 4-2. Summary of chemical dosing scenarios for alum and PACl comparison	4-22
Table 4-3. Raw water and filter effluent particle counts summary, averaged by individual runs conducted during the side-by-side testing of alum and PACl with no filter aid, from July 30 – August 5.....	4-31
Table 4-4. Raw water and filter effluent particle counts summary, averaged by individual runs conducted during the side-by-side testing of alum and PACl with filter aid, from August 5 –12	4-34
Table 4-5. Raw water and filter effluent particle counts summary, averaged by accepted filter runs during side-by-side testing of alum and PACl following ozone pre-oxidation, conducted August 20 – 30	4-37
Table 4-6. Pilot-scale Ozone Decay Kinetics ^(a)	4-46
Table 4-7. Raw water and filter effluent particle counts summary, averaged by accepted filter runs during side-by-side testing of pre-oxidation vs. no pre-oxidation, conducted August 30 – September 30	4-49
Table 4-8. Average organics removal during pre-ozonation vs. no pre-oxidation testing from August 30 through September 29	4-55
Table 4-9. Raw water and filter effluent particle counts summary, averaged by accepted filter runs during side-by-side testing of ozone vs. chlorine pre-oxidation, conducted October 14 – 18.....	4-61
Table 4-10. Average Organics Removal during pre-chlorination vs. pre-ozonation testing from October 14–October 18	4-66
Table 5-1. Theoretical Clean Bed Head Loss	5-2
Table 5-2. Filter Turbidity During Summer Season (July-Sep)	5-5
Table 5.3. Filter Turbidity During Fall Season (Oct)	5-5
Table 6-1 Post-Filtration Treatment Targets used in October SDS Testing	6-2

List of Abbreviations

ACH	aluminum chlorohydrate	mgd	million gallons per day
Alum	hydrated aluminum sulfate	MRL	method reporting limit
AOC	assimilable organic carbon	MUL	maximum use limit
ATP	adenosine triphosphate	NPDES	National Pollutant Discharge Elimination System
AWOP	OHA's Area-Wide Optimization Program	NSF	NSF International
AWWA	American Water Works Association	NTU	nephelometric turbidity unit
BC	Brown and Caldwell	OHA	Oregon Health Authority
CaCO ₃	calcium carbonate	OSHA	Occupational Safety and Health Administration
CBHL	clean bed head loss	PACl	polyaluminum chloride
CDD	chlorine demand and decay	pg	picogram
CFE	combined filter effluent	PID	proportional integral derivative
CU	University of Colorado	P&ID	process and instrumentation diagram
DBP	disinfection by-products	PSW	Partnership for Safe Water
DF	direct filtration	Pt-Co	Platinum cobalt units
DOC	dissolved organic carbon	PWB	Portland Water Bureau
EPA	U.S. Environmental Protection Agency	QA/QC	quality assurance and quality control
FE	filter effluent	scfm	standard cubic feet per minute
Ferric	ferric chloride	SCM	streaming current monitor
FI	filterability index	SDS	simulated distribution testing
FTW	filter-to-waste	SLR	surface loading rate
GAC	granular activated carbon	SM	Standard Method
gpd	gallons per day	SOP	standard operating procedure
gph	gallons per hours	SOR	surface overflow rate
gpm	gallons per minute	TAC	technical advisory committee
HAA5	sum of 5 haloacetic acids	TOC	total organic carbon
HPLC	high performance liquid chromatography	TSS	total suspended solids
HMI	human machine interface	TTHM	total trihalomethanes
ICCT	improved corrosion control treatment	UFRV	unit filter run volume, gallon/sf-run
ICPMS	inductively coupled plasma mass spectrometry	UVA	ultraviolet absorbance
IQR	interquartile range	UV ₂₅₄	ultraviolet absorbance at 254 nanometers, m-1
lf	linear feet	UVT	ultraviolet transmittance
L/d	length to diameter ratio		
LRAA	locational running annual average		
MCL	maximum contaminant level		
µg/L	micrograms per liter		
µm	micrometer or micron		
MDL	minimum detection limit		

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Executive Summary

This Draft Interim Pilot Study Report (Report) describes the pilot testing that was conducted for the Portland Water Bureau (PWB) to aid the planning and designing of a new greenfield water filtration facility, referred to as the Bull Run Filtration Facility (Filtration Facility), which is scheduled to be in service in 2027. This Report is an interim document that covers the first part of the pilot study period from June 2019 to October 2019. The Final Pilot Study Report will cover a full 12-month study period.

The pilot study is part of the overall Bull Run Treatment Program to meet the requirement of providing pilot study results to the Oregon Health Authority (OHA) by November 2020 (OAR 333-061-0050). The pilot study will inform a proposed treatment approach and design for the Filtration Facility. The pilot study is focused on the evaluation of pre-treatment ahead of granular media filtration and granular media filtration itself.

In preparation for the pilot study, the 2019 Pilot Plant Work Plan (Work Plan) was prepared by Brown and Caldwell (BC) detailing the tasks to be completed during phase one of the pilot study. The Work Plan was reviewed by OHA in April 2019 and finalized in May (BC 2019). The Work Plan provided a framework for the pilot testing, including an overview of the testing schedule, pilot plant location and site development, and equipment operation, and the plan for water quality data collection. Based on operational findings and pilot testing results, the pilot testing schedule was adjusted as needed.

The main objectives of the pilot study include:

- Inform treatment process selection for the Filtration Facility,
- Support development of a sound, buildable, and operable basis of design for the Filtration Facility that meets regulatory requirements,
- Inform design parameters and seasonal operating parameters,
- Evaluate data for consistency and potential future considerations of Partnership for Safe Water (PSW)/OHA's Area-Wide Optimization Program (AWOP), and
- Serve as an educational tool for engineers and operators, and engagement in treatment process understanding.

The pilot study has developed several water treatment goals and benchmarks summarized in Table ES-1. The operational goals for turbidity are based on PSW Phase IV Performance Goals (PSW 2014) and OHA's AWOP. Particle counts are being used as a surrogate to demonstrate removals of *Cryptosporidium* oocysts (3- to 5-micrometer [μm] diameter) and *Giardia* cysts (5- to 15- μm diameter) in the filtered water. The goals for disinfection by-products (DBPs) are that total trihalomethanes (TTHMs) and haloacetic acids (HAA5s) are less than half the maximum contaminant level (MCL).

Table ES-1. Pilot Study Water Quality Goals and Performance Benchmarks

Parameter	Location	Regulatory Requirement ^a	Operational Goal ^b	Comments on Operational Goal
Turbidity	Settled water ^c	No requirement	≤ 2.0 nephelometric turbidity unit (NTU), 95% of monthly samples ^d	Overview of PSW and OHA's AWOP Program: ≤ 1.0 NTU, 95% of the time when source turbidity ≤ 10 NTU, and ≤ 2.0 NTU, 95% of the time when source water turbidity > 10 NTU.
	Individual filter effluent (FE) ^e	≤ 0.3 NTU, 95% of the monthly samples ^f	≤ 0.10 NTU, 95% of the filter run time	Operational goal matches PSW Phase IV Performance goal but more stringent because it is applied to Individual FE; OHA's AWOP operational goal is below LT2 Microbial Toolbox credit of 0.15 NTU.
	Individual FE ^e	≤ 1 NTU at any time ^f	≤ 0.30 NTU, 100% of the filter run time	Operational goal matches PSW Phase IV Performance Goal; OHA's AWOP.
Particle counts	Individual FE ^e	No requirement	< 50 particles/mL at 5–15 µm, 95% of the filter run time or	Particle count goals are surrogates for Cryptosporidium and Giardia removal.
	Individual FE ^e compared to raw		2.0-log removal from raw water for 3–5 µm and 2.5-log removal for 5–15 µm ^g	Particle count goals are surrogates for Cryptosporidium and Giardia removal; assumes sedimentation in operation.
Total trihalomethanes (TTHM)	Simulated distribution system (SDS)	Maximum contaminant level (MCL) = 80 micrograms per liter (µg/L)	≤ 40 µg/L for chosen treatment scheme based on DBP SDS testing	Operational goal based on Locational Running Annual Average (LRAA); operational goal (half MCL) is also trigger for reduced DBP monitoring.
Sum of 5 haloacetic acids (HAA5)	SDS	MCL = 60 µg/L	≤ 30 µg/L for chosen treatment scheme based on DBP SDS testing	
Minimum Unit Filter Run Volume (UFRV)	Individual filter	No requirement	> 6,500 gallon/sf-run, 95% of the operational time ^h	Backwash based on turbidity, head loss, and run time triggers; operational goal is based on estimated minimum to meet water production goals.
Filter-to-waste (FTW) Cycle	FTW	No requirement	≤ 5% of total UFRV, 95% of the operational time	Operational goal based on wanting to achieve an overall filter efficiency of at least 95%.

a. Regulatory requirement meets federal and state requirements.

b. The operational goal is modeled from PSW and OHA's AWOP and is an internal PWB goal, not based on regulatory requirements.

c. Applicable when operating in conventional filtration mode.

d. Optimal turbidity will be determined based on producing filterable floc. This goal may require turbidities greater than 1 NTU when raw water turbidity is less than 10 NTU.

e. Individual FE samples will be analyzed continually and recorded every 5 minutes.

f. Regulatory requirement is based on combined filter effluent (CFE). Pilot study monitoring based on individual FE.

g. When operating in direct filtration mode, 2.0-log removal from raw water for 3–5 µm range and for 5–15 µm range.

h. UFRV is based on a filter loading rate of 12 gallons per minute (gpm) per square foot (sf) and a desired plant production of 145 million gallons per day (mgd) with 8 filters and 1 filter out of service.

Summary of Testing

Table ES-2 below summarizes testing conducted from July through October 2019. Prior to start-up of the pilot plant, PWB and BC staff conducted bench-scale testing, including jar testing, to evaluate coagulants and polymers. In addition, bench-scale ozone testing was conducted by BC and University of Colorado to inform start-up conditions for the ozone module and to understand ozone demand and decay behavior. The pilot plant was wet-tested starting in late May 2019, to test the pilot plant with only water through the plant, prior to the addition of chemicals. The next month consisted of start-up and commissioning. Continuous operation officially started on July 1 with a period of coagulation testing and selection.

During the summer season, the focus was to ramp up to the higher filtration rates (12 gal per minute [gpm] per square foot [sf] and 8 gpm/sf) and to compare a suite of coagulants and treatment chemicals from which a preferred chemical configuration would be selected. Once the coagulant selection was complete, ozonation was tested starting with pre-ozonation. Over the first half of October, an initial trial of direct filtration (DF) vs. conventional filtration was conducted, followed by the start of a more detailed comparison of pre-oxidants with conventional filtration. In addition to the pilot testing, SDS testing was performed to evaluate potential DBP formation.

Table ES-2. Summary of testing scenarios for pilot plant study from July 1 to October 31		
Test Duration	Testing Scenario	Conditions
July 1 to August 30	Coagulant testing of alum, ferric chloride, PACl, and ACH ^a over two months	Tested various chemical dosages of coagulants, coagulant aid, and filter aid.
August 30 to September 29	Pre-oxidation testing with pre-ozonation vs. no pre-oxidation for one month	Dose of 0.5 mg/L ozone (O ₃) followed by a period with an increased ozone dose of 1.0 mg/L O ₃ . PACl with filter aid and no coagulant aid for both trains.
September 30 to October 11	DF testing with pre-ozonation for two weeks	DF vs. conventional treatment with pre-ozonation dose of 1.0 mg/L O ₃ , PACl with filter aid and no coagulant aid for both trains.
October 14 to 21	Pre-chlorination testing with pre-chlorine vs. pre-ozonation over one week	Chlorine dose of 0.3 mg/L Cl ₂ and ozone dose of 1.0 mg/L. PACl with filter aid and no coagulant aid for both trains.
July 1 to October 31	Filter Design	Filter loading rates and media type with various pre-treatment conditions.

a. Coagulants include the following: Hydrated aluminum sulfate (alum), polyaluminum chloride (PACl), ferric chloride (Ferric), aluminum chlorohydrate (ACH)

Coagulant Selection

Four primary coagulants (alum, ferric chloride, PACl, and ACH) were evaluated during bench- and pilot-scale testing. PACl and alum both performed well at the pilot-scale in terms of filter productivity and organics removal. PACl was selected as the primary coagulant for further testing during the fall season because it performed as well as, if not better than, alum and did not require supplemental alkalinity as alum did, for successful coagulation.

Pre-ozonation

Pre-ozonation demand and decay studies were conducted at bench- and pilot-scale. A demand and decay model was developed to fit the pilot ozone applied and residual data using a two-step exponential algorithm based on the approach of Haas and Karra (1984). This ozone decay model is presented in Table ES-3 for Trains 1 and 2. During the fall season of ozone testing when organics are highest, an applied ozone dose of 1 mg/L resulted in an ozone residual of less than 0.1 mg/L after an ozone contact time of 8 minutes.

Table ES-3. Pilot-scale Ozone Decay Kinetics ^(a)

Parameter	Variable	Train 1	Train 2
Dual Rate Constant ^(b)	High Rate (k ₁)	0.32	0.32
	Low Rate (k ₂)	0.04	0.11
	A	0.95	0.97
	R ² ^(c)	0.99	0.99
Number of Samples		1,512	3,034

a. Temperatures ranged from 11°C to 15°C over the period of data collection.

b. 1st Order Split Rate Constant Equation: $C = C_0 e^{-k_l t} + (1 - A)C_0 e^{-k_h t}$, where t = time (min), C_0 = initial concentration (mg/L), C = final concentration (mg/L), k_l and k_h = computed decay constants (min⁻¹), and A is a value less than one that determines the regions of high and low rates.

c. R² values were evaluated using the sum of residual squares

Pre-ozonation significantly improves filter productivity. On average, the 50th percentile UFRVs with pre-ozonation were 1.5 times greater than the filters with no pre-oxidant. The UFRVs on both trains exceeded the goal of 6,500 gal/sf-run during 95 percent of the operational time. All of the filters' 50th percentiles were at or greater than 10,000 gal/sf-run.

Median and 95th percentile filter effluent particle counts were higher with pre-ozonation compared to no pre-oxidant. However, this was attributable to observed particle breakthrough at the end of filter runs on the train with pre-ozonation pretreatment, behavior which was not observed on the train without pre-oxidation. All but one filter met the goal of having less than 50 particles/mL in the 5 to 15 µm range (95 percent of the time). The pre-ozonated anthracite filter at 12 gpm/sf (Filter 1) was just slightly above that goal with a 95th percentile value of 56 particles/mL.

Pre-ozonation improved UV₂₅₄ removal (an average of 92 percent in the ozonated train compared to 78 percent in the train with no pre-oxidant). Both trains showed good color removal (greater than 50 percent) and TOC removal (approximately 50 percent).

Prechlorination

Pre-ozonation and prechlorination had comparable filtration performance. All of the filters exceeded the water production goal for a UFRV in excess of 6,500 gal/sf-run, 95 percent of the time. In almost all cases, the median value of the UFRVs exceed 10,000 gal/sf-run (except for the pre-chlorinated GAC filter operating at 12 gpm/sf). Pre-chlorination tended to have fewer particles in the filtered water than pre-ozonation, but testing will continue when pre-treatment is better adjusted for raw water conditions.

Prechlorination removed organics during the testing period, but pre-ozonation performed slightly better, showing 90 percent removal of UV₂₅₄ compared to 82 percent removal for the pre-chlorinated train. Both trains removed a similar amount of TOC (approximately 50 percent).

Filter Performance

Filter performance was evaluated for differing filtration rate and filter media over the entire test regime. There were many different operational conditions over the entire test regime, so this section draws some general conclusions.

All of the filters had low levels of filtrate turbidity. All of the 6 filters met the water quality goal in the summer and fall seasons to have the 95th percentile turbidity in the individual filter effluent be less than 0.1 NTU.

UFRVs from acceptable filter runs for the first four months of operations were compared at the different filtration rates to understand if there was a difference in performance based on filtration rate. On average, the filters operating at 8 gpm/sf had higher UFRVs than the filters operating at 12 gpm/sf. All of the filters' median UFRV exceeded 10,000 gal/sf-run. Except for filter 1, all of the filters' minimum value of the representative filter runs was above the UFRV goal of 6,500 gal/sf-run.

Organics removal was comparable at both filtration rates; low (6 and 8 gpm/sf) and high (8 and 12 gpm/sf), revealing that higher filtration rates did not result in worse organic removal performance.

For the filters operating at 12 gpm/sf, the anthracite media filters had higher UFRVs than the GAC filters. The GAC filters removed more organics than the anthracite filters, but both media had good organics removal. The observed organics removal in the anthracite columns generally averaged between 40 to 50 percent. TOC removal was somewhat higher in the GAC columns during the test period, but this may be attributable to the use of virgin GAC for the filters, which means that the adsorptive capacity of the GAC had not yet been exhausted. The differential in TOC removal between the anthracite and GAC filters decreased over the duration of the test period, suggesting that the adsorptive capacity of the GAC may have begun to diminish as available adsorption sites were occupied. Given the fact that filtration performance was better in the anthracite filters and the anthracite filters had good organics removal, it is recommended that the GAC media be swapped with additional anthracite media to allow for more scrutiny of the effective size, media depth, and filter loading rates.

Chapter 1

Introduction

This Draft Interim Pilot Study Report (Report) describes the pilot testing that was conducted for the Portland Water Bureau (PWB) Bull Run Supply to assist them in transitioning to a new greenfield water filtration facility, referred to as the Bull Run Filtration Facility (Filtration Facility) scheduled to be in service in 2027. This Report is an interim document that covers the first part of the pilot study period from June 2019 to October 2019. The Final Pilot Study Report will cover a full 12-month study period.

The pilot study is part of the overall Bull Run Treatment Program to meet the requirement of providing pilot study results to the Oregon Health Authority (OHA) by November 2020 (OAR 333-061-0050). The pilot study will inform a proposed treatment approach and design for the Filtration Facility. The pilot study is focused on the evaluation of pre-treatment ahead of granular media filtration and granular media filtration itself.

In preparation for the pilot study, the 2019 Pilot Plant Work Plan (Work Plan) was prepared detailing the tasks to be completed during phase one of the pilot study. The Work Plan was reviewed by OHA in April 2019 and finalized in May (BC 2019). The Work Plan provided a framework for the pilot testing, including an overview of the testing schedule, pilot plant location and site development, and equipment operation, and the plan for water quality data collection. Based on operational findings and pilot testing results, the pilot testing schedule was adjusted as needed.

1.1 Document Structure

This interim report is organized as follows:

- Chapter 1 – Introduction; Background, Pilot Study Objectives, Water Treatment Goals, Test Plan
- Chapter 2 – Pilot Plant Configuration
- Chapter 3 – Raw Water Quality Characteristics
- Chapter 4 – Pilot Study Results
 - 4.1 – Filter Operation
 - 4.2 – Coagulant Testing and Selection
 - 4.3 – Pre-oxidant Testing
 - 4.4 – Direct Filtration Testing
- Chapter 5 – Filter Performance Comparison
 - 5.1 – Clean Bed Head Loss
 - 5.2 – UFRVs
 - 5.3 – Organics Removal
 - 5.4 – Biological Activity Monitoring
- Chapter 6 – Chlorine Demand/Decay and DBP Testing
- Chapter 7 – Summary of Interim Pilot Plant Study Results

1.2 Background

The pilot study is evaluating several treatment approaches including, but not limited to, pre-oxidation, conventional and direct filtration (DF), filtration media type, filtration media depth, and filtration loading rates. Conventional filtration includes four discrete unit processes: rapid mix for chemical coagulant dispersion, flocculation, sedimentation, and filtration. DF is the same process train but with the sedimentation process eliminated. In addition, pre-ozonation will be tested for the ability to improve filtration performance and to evaluate how ozonation followed by biofiltration impacts the removal of natural color, organics, inorganics, and disinfection by-product (DBP) precursors. In addition, pre-chlorination will be evaluated against pre-ozonation during the pilot study to compare filtration performance and removal of organics, DBP formation, color, and inorganics, such as manganese to pre-ozonation and intermediate ozonation. This study is also evaluating each specific unit process with respect to removal of particulates, organics, and the treatment process train's overall ability to comply with current regulatory requirements and guidance from PSW Phase IV Performance Goals (PSW 2014) and OHA's AWOP. Furthermore, the study will be completed over 12 months to evaluate performance across seasonal variation in raw water quality.

1.3 Pilot Plant Study Objectives

The main objectives of the pilot study include:

- Inform treatment process selection for the Filtration Facility,
- Support development of a sound, buildable, and operable basis of design for the Filtration Facility that meets regulatory requirements,
- Inform design parameters and seasonal operating parameters,
- Evaluate data for consistency and potential future considerations of PSW/OHA's AWOP, and
- Serve as an educational tool for engineers and operators, and engagement in treatment process understanding.

The pilot study will inform the following design criteria:

- Pre-oxidant type, dosing location, contact time, and dose
- Alkalinity and pH adjustments ahead of coagulation
- Coagulant and coagulant aid type and dose range, and addition points for coagulant aid
- Filter aid type and dose range
- Unit filtration rate
- Filter media type and bed configuration (depth)
- Primary and secondary disinfectant dose (free chlorine will be the primary disinfectant with the possibility of credit for ozonation upstream of filtration, and secondary disinfection will be achieved with chloramines)
- Residual management strategies

1.4 Water Treatment Goals

The pilot study treatment goals and benchmarks are presented in Table 1-1 below, which provides the regulatory requirement (if one exists) for the given parameter, and the corresponding operational goal. The operational goals for turbidity are based on PSW Phase IV Performance Goals (PSW 2014) and OHA's AWOP.

A common surrogate for *Cryptosporidium* and *Giardia* removal are particle counts. Particle counters detect the number of particles at one time for a designated particle diameter. By setting the particle diameter to sizes characteristic of microorganisms, particle counts can be used as a surrogate to demonstrate *Cryptosporidium* oocysts (3- to 5-micrometer [μm] diameter) and *Giardia* cysts (5- to 15- μm diameter) removal.

When source water particle concentrations are low, it is often difficult for treatment processes to attain 2- to 2.5-log particle reductions even though excellent finished water clarity is being achieved (Gong et al. 1993; Yorton et al. 1993). The magnitude of log removal is affected by the number of particles in the source water. A particle count limit of less than 50 particles per milliliter (particles/mL) in the 5- to 15- μm range was established as an acceptable method to overcome this concern based on LeChevallier and Norton (1992). LeChevallier and Norton's study found that the occurrence of parasites in plant effluent samples could be related to particle counts greater than 50 particles/mL for particles sized greater than 5 μm (LeChevallier and Norton 1992). A similar particle count limit for the size range related to *Cryptosporidium* oocysts (3 to 5 μm) was not established in the text plan because this size range was not included in LeChevallier and Norton (1992) nor was a similar relationship between oocyst occurrence and particle counts found in the literature.

Organics removal was evaluated through each treatment process and is discussed in the subsequent sections. Enhanced coagulation to remove organics is required if the Total Organic Carbon (TOC) levels in the raw water exceed 2.0 milligrams per liter (mg/L). For PWB's water supply, raw water annual average TOC levels were less than 2.0 mg/L historically and were below 0.9 mg/L on average for the first 4 months of pilot operations from July to October 2019. Based on the historical and most recent TOC levels, enhanced coagulation is not required for the full-scale Filtration Facility, and therefore is not required for pilot testing.

Table 1-1. Pilot Study Water Quality Goals and Performance Benchmarks

Parameter	Location	Regulatory Requirement ^a	Operational Goal ^b	Comments on Operational Goal
Turbidity	Settled water ^c	No requirement	≤ 2.0 nephelometric turbidity unit (NTU), 95% of monthly samples ^d	Overview of PSW and OHA's AWOP Program: ≤ 1.0 NTU, 95% of the time when source turbidity ≤ 10 NTU, and ≤ 2.0 NTU, 95% of the time when source water turbidity > 10 NTU.
	Individual filter effluent (FE) ^e	≤ 0.3 NTU, 95% of the monthly samples ^f	≤ 0.10 NTU, 95% of the filter run time	Operational goal matches PSW Phase IV Performance goal but more stringent because it is applied to Individual FE; OHA's AWOP operational goal is below LT2 Microbial Toolbox credit of 0.15 NTU.
	Individual FE ^e	≤ 1 NTU at any time ^f	≤ 0.30 NTU, 100% of the filter run time	Operational goal matches PSW Phase IV Performance Goal; OHA's AWOP.
Particle counts	Individual FE ^e	No requirement	< 50 particles/mL at 5–15 µm, 95% of the filter run time or	Particle count goals are surrogates for Cryptosporidium and Giardia removal.
	Individual FE ^e compared to raw		2.0-log removal from raw water for 3–5 µm and 2.5-log removal for 5–15 µm ^g	Particle count goals are surrogates for Cryptosporidium and Giardia removal; assumes sedimentation in operation.
Total trihalomethanes (TTHM)	Simulated distribution system (SDS)	Maximum contaminant level (MCL) = 80 micrograms per liter (µg/L)	≤ 40 µg/L for chosen treatment scheme based on DBP SDS testing	Operational goal based on Locational Running Annual Average (LRAA); operational goal (half MCL) is also trigger for reduced DBP monitoring.
Sum of 5 haloacetic acids (HAA5)	SDS	MCL = 60 µg/L	≤ 30 µg/L for chosen treatment scheme based on DBP SDS testing	
Minimum Unit Filter Run Volume (UFRV)	Individual filter	No requirement	> 6,500 gallon/sf-run, 95% of the operational time ^h	Backwash based on turbidity, head loss, and run time triggers; operational goal is based on estimated minimum to meet water production goals.
Filter-to-waste (FTW) Cycle	FTW	No requirement	≤ 5% of total UFRV, 95% of the operational time	Operational goal based on wanting to achieve an overall filter efficiency of at least 95%.

a. Regulatory requirement meets federal and state requirements.

b. The operational goal is modeled from PSW and OHA's AWOP and is an internal PWB goal, not based on regulatory requirements.

c. Applicable when operating in conventional filtration mode.

d. Optimal turbidity will be determined based on producing filterable floc. This goal may require turbidities greater than 1 NTU when raw water turbidity is less than 10 NTU.

e. Individual FE samples will be analyzed continually and recorded every 5 minutes.

f. Regulatory requirement is based on combined filter effluent (CFE). Pilot study monitoring based on individual FE.

g. When operating in DF mode, 2.0-log removal from raw water for 3–5 µm range and 2.0-log removal for 5–15 µm range.

h. UFRV is based on a filter loading rate of 12 gallons per minute (gpm) per square foot (sf) and a desired plant production of 145 million gallons per day (mgd) with 8 filters and 1 filter out of service.

The following sections provide an overview of pilot testing completed through October 2019 (Section 1.5.1) and planned testing for the remaining portion of the study (Section 1.5.2). The following processes are being investigated in the study:

- DF vs. conventional filtration
- Pre-ozonation or intermediate ozonation and/or additional pre-oxidants
- Granular media filtration rate with four differing filter media configurations

1.5 Test Plan

This section provides a summary of testing completed in phase one of the pilot plant study, as reported in this Interim Report, followed by the proposed test plan for the remainder for the study.

1.5.1 Summary of Testing Through October 2019

Figure 1-1 below summarizes testing conducted from February 2019 through October 2019, showing the key testing periods, as well as the timing of supplemental testing including bench-scale jar testing, ozone demand-decay testing, coagulant selection, and SDS testing.

Prior to start-up of the pilot plant, PWB and BC staff conducted bench-scale testing, including jar testing, to evaluate coagulants and polymers. In addition, bench-scale ozone testing was conducted by BC and University of Colorado to inform start-up conditions for the ozone module and to understand ozone demand and decay behavior. The pilot plant was wet-tested starting in late May 2019, to test the pilot plant with only water through the plant, prior to the addition of chemicals. The next month consisted of start-up and commissioning. Continuous operation officially started on July 1 with a period of coagulation testing and selection.

During the summer season, the focus was to ramp up to the higher filtration rates (12 gpm per square foot [sf] and 8 gpm/sf) and to compare a suite of coagulants and treatment chemicals from which a preferred chemical configuration would be selected. Once the coagulant selection was complete, ozonation was tested starting with pre-ozonation. Over the following month, an initial trial of direct vs. conventional filtration was conducted, followed by the start of a more detailed comparison of pre-oxidants with an evaluation of pre-ozonation vs. pre-chlorination.

In addition to the pilot testing, SDS testing was performed to evaluate potential DBP formation. Additional SDS testing was conducted in November 2019 in conjunction with PWB's DBP compliance sampling, and will be conducted quarterly thereafter. Results from the SDS testing are summarized in Chapter 6.

Phase	2019									
	Winter		Spring			Summer			Fall	
	Feb	March	April	May	June	July	Aug	Sept	Oct	
Bench-scale jar testing	▲	▲	▲							
Bench-scale ozonation	▲									
Start-up and Training										
Coagulant Testing										
Train 1 - Flocc/Sed Unit										
Pre-oxidant Testing										
Filter 4: GAC, 72 inches										
Filter 5: anthracite, 60 inches										
Filter 6: anthracite, 72 inches										
Train 2 - Flocc/Sed Unit										
Pre-oxidant Testing										
Filter 1: anthracite, 72 inches										
Filter 2: GAC, 60 inches										
Filter 3: GAC, 72 inches										
SDS Testing										▲

Abbreviations

- O₃ = Pre-ozonation. Use of ozone as an oxidant before flocculation/sedimentation process
- Cl₂ = Pre-chlorination. Use of chlorine as an oxidant before flocculation/sedimentation process
- Conven = Conventional treatment
- ▲ Month of testing

Figure 1-1. Summary of Pilot Testing from February through October 2019

1.5.2 Summary of Testing Planned Through June 2020

The duration of the pilot study will be focused on testing the remaining pilot objectives and evaluating the testing regimes across the seasons. Some tests that were conducted during the first 4 months of the study will be repeated to collect additional data. The proposed experiments are subject to change over time, as pilot plant data become available and necessary modifications are made to respond to testing outcomes.

The following experiments are proposed over the next three seasons:

Fall Season Testing (October – December)

- Pre-ozonation vs. no pre-oxidant
- Pre-chlorination vs. no pre-oxidant
- Pre-ozonation vs. pre-chlorination

Winter Season Testing (January – March)

- Test new anthracite media configurations
- Turbidity spiking with low alkalinity, cold water
- Pre-ozonation vs. intermediate ozonation

Spring Season Testing (April – June)

- Pre-ozonation vs. intermediate ozonation
- Varied filtration rates
- Flocculation adjustments (e.g. detention time, floc mixer type, etc.)
- Testing with the preferred oxidant approach (pre-ozonation vs. intermediate ozonation, ozone vs. chlorine, etc.)

Chapter 2

Pilot Plant Configuration

Based on a collaborative pilot design process between BC's treatment experts, PWB staff, and the Technical Advisory Committee (TAC), the following treatment processes were selected for the pilot study in a dual train configuration:

- Rapid mix
- Flocculation alone (DF)
- Flocculation and sedimentation (conventional)
- Ozonation (pre-ozonation and intermediate ozonation), as well as chlorine
- Granular media filtration
- Solids handling system (equalization basin and settling tank) to handle wastes from the pilot system

Figure 2-1 below shows the process flow diagram for the pilot plant facilities including two treatment trains in parallel (Train 1 and Train 2). Each treatment train is served by a flocculation-sedimentation system, ozone module, and filtration skid. Two flocculation and sedimentation units are used so DF and conventional filtration can be compared simultaneously. The pilot units are configured so sedimentation can be bypassed. This enables one flocculation and sedimentation pilot unit to be operated in either direct or conventional filtration mode. There is also an option to bypass individual cells of the three-cell flocculation system (to vary flocculation detention time) and/or the sedimentation system for direct filtration. The ozone unit is configured so that pre-ozonation and intermediate ozonation can be tested in either train. Six filters are included to test different media configurations, as shown in Table 2-1.

Additional media details are provided in Section 2.3.1.

Table 2-1. Six-Filter Configuration		
Train	Filter number	Media type
Train 1	4	Granular activated carbon (GAC)/sand
	5	Anthracite/sand
	6	Anthracite/sand
Train 2	1	Anthracite/sand
	2	GAC/sand
	3	GAC/sand

The treatment chemicals are all NSF-60 approved for potable water consumption and are used at doses below the NSF-60 potable water maximum use limit (MUL).

The filtered water from the six filters is sent to a backwash storage tank to serve as a backwash water source. Wash water, filter-to-waste, and solids residual from the sedimentation process are managed by an equalization basin followed by liquid-solids separation in a large settling tank, similar to a gravity thickener, referred to as the solids handling system.

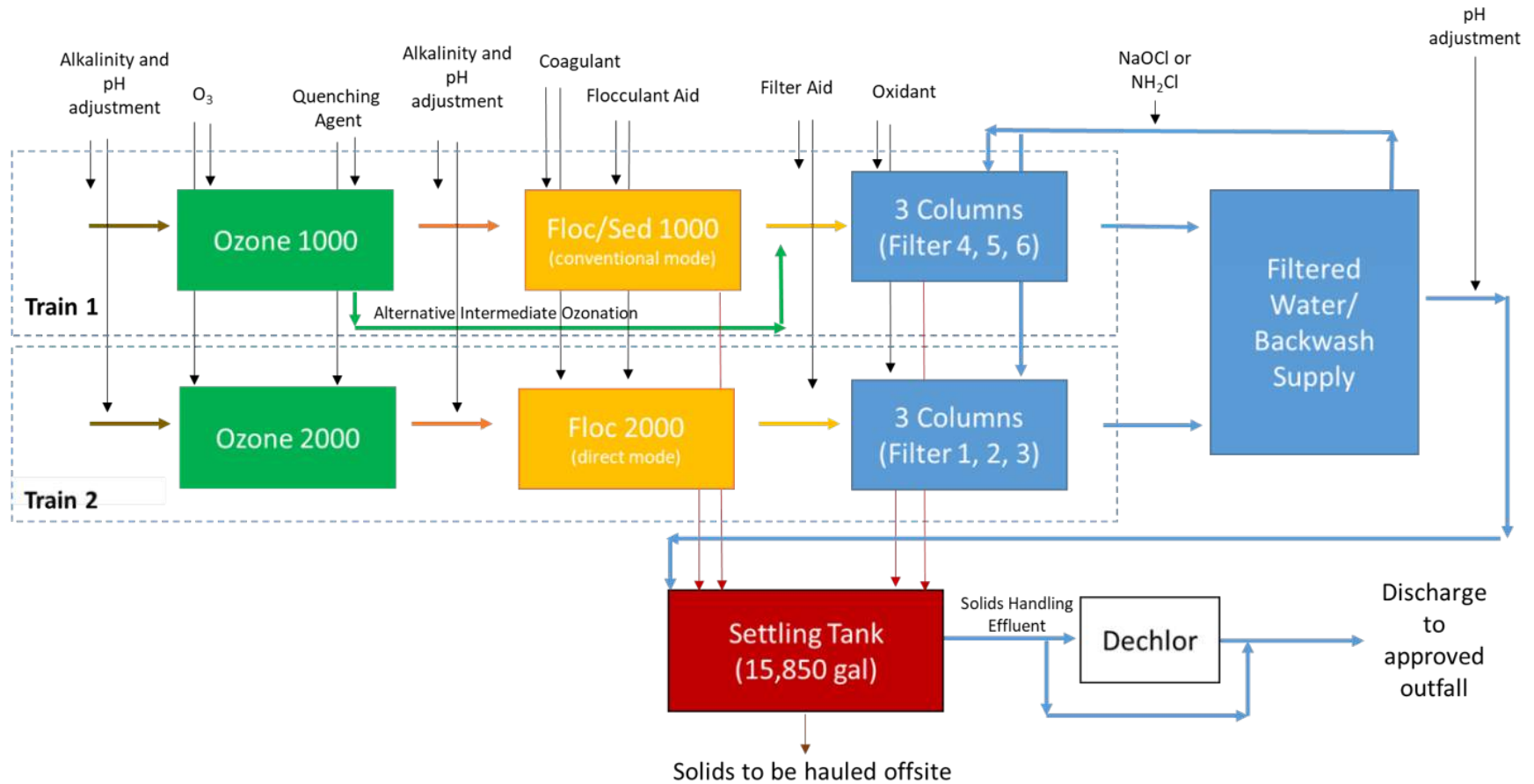


Figure 2-1. PWB pilot plant dual train process flow diagram

Excess filtered water is also sent to the solids handling system. In addition, excess settled water from the sedimentation process overflows to a waste line directed to the solids handling system. Effluent from the settling tank is combined with excess filtered water from the filtered water line, and is ultimately discharged to the Bull Run River and monitored for discharge characteristics and requirements.

The settled solids (i.e., sludge) from the settling tank will accumulate and thicken in the tank. When needed, solids from the settling basin can be pumped out of the tank by a Vactor truck for hauling off-site and disposal. When investigating chlorination, effluent from the settling tank is routed through a dichlorination unit (GAC contactor) prior to Bull Run River discharge. The solids handling system is designed to handle the pilot wastes but does not mimic a full-scale solids handling system, and therefore, will not inform full-scale design directly.

2.1 Flocculation and Sedimentation Pilot Unit

The flocculation-sedimentation pilot unit includes a three-stage rapid mix system, three-stage flocculation system, and a plate settler with removable settling plates (i.e., sedimentation basin). Figure 2-2 shows the front and back side of the Floc Sed 1000 module at the pilot plant.



Figure 2-2. Intuitech flocculation-sedimentation module 1000 (model S300) at the pilot plant

Left: Shows the side of the unit with viewports into the flocculation and sedimentation basins.

Right: Shows the side of the unit with the instrumentation, chemical tanks, and human-machine interface (HMI).

The rapid mix, flocculation, and sedimentation unit are operated using the control panel. Adjustable variable speed mixers are provided for individual rapid mix stages and the tapered flocculation stages, allowing for the adjustment of velocity gradients in the mixing vessels. Detention times in the flocculation process can be varied by bypassing one or more of the individual flocculation stages or by varying inlet flow. The system can also operate in a direct-filtration mode by bypassing the sedimentation basin.

Sedimentation surface loading rates (SLR) are varied by physically adding or removing inclined plate settlers to affect hydraulic unit loading, allowing to test both high- and low-rate sedimentation operations.

Coagulant and coagulant aid chemicals are dosed at the rapid mix system to facilitate colloidal destabilization, but can also be added to each stage of flocculation, if desired. The chemicals can be flow paced or pH controlled. Coagulant and coagulant aid were flow paced for this study.

2.2 Ozonation Pilot Unit

The ozonation pilot unit consists of two contact chambers and two feed pumps. The unit has the flexibility to run in series or parallel depending on the objectives of the study. The ozone generator is air-cooled with an integral oxygen concentrator for creating ozone from ambient air. Each contact chamber contains over-under baffles with five chambers. Ozone can be applied either at the inlet, or either chamber through a fine bubble diffuser controlled by a common control panel. The feed to the unit is controlled by an automatic proportional–integral–derivative (PID) flow control. Figure 2-3 shows the ozonation module (model Z300) at the pilot plant.



Figure 2-3. Intuitech ozonation module (model Z300) at the pilot plant

The ozonation unit is also used for additional oxidant applications and comparisons, such as sodium hypochlorite. Four chemical feed systems are located at the ozone unit, providing a variety of options for oxidant injection locations as well as quenching agents.

2.3 Filtration Pilot Unit

The filtration pilot units consist of six filter columns. The six filters are operated simultaneously, with three filters per train. Filter influent and water used for backwashing was not chlorinated during this investigation, therefore the filters were able to operate as biologically active filters.

Figure 2-4 shows the Intuitech six-filter unit (model F300) at the pilot plant. The unit includes an individual feed pump for each filter column, a backwash system, and an air scour system. Each filter flows independently. Only one filter can be backwashed at a time, but filters can be backwashed sequentially (one after the other). Filter backwashing can be controlled manually or initiated automatically based on run time, head loss, or effluent turbidity measurement setpoints. More information on filter backwash setpoints is provided below in Section 2.3.2. In addition, the unit provides nine chemical feed systems for the ability to feed filter aid, pre-oxidants, or reducing agents to all six filters, to specific process trains, or to individual filters. The chemicals can be flow paced or pH controlled. Filter aid was flow paced for this study.



Figure 2-4. Intuitech 6-column filtration module, model F300 at the pilot plant

2.3.1 Filter Media Configuration

Table 2-2 lists the filter media configuration for the six filters. The GAC media selected for pilot testing was the Calgon Filtrasorb 816. BC selected the proposed anthracite media profile to have a similar effective size and length to diameter ratio (L/d) as the GAC media.

Two media configurations were decided on for the high-rate filters: (1) a total media depth of 72 inches for a typical filter loading rate of 10 to 12 gpm/sf, and (2) a total media depth of 60 inches for an typical filter loading rate of 8 gpm/sf to 10 gpm/sf. One key design criterion for filtration design is the L/d ratio:

$$\frac{L}{d} \text{ ratio} = \frac{\text{Bed depth, } L}{\text{Effective size, } d_{10}}$$

Industry practice is to choose an L/d ranging between 1,500 and 2,000. The proposed L/d for the anthracite and GAC medias are 1,640 and 1,730, respectively, for the 72 inches of total media depth. The proposed L/d for the anthracite and GAC medias are 1,530 and 1,500, respectively, for the 60 inches of total media depth. The media used for the filter columns was sent to AWI, Anthratch U.S. Inc., for sieve analysis to confirm pilot tested media characteristics. The results of the media sieve analysis are presented in Table 2-2.

Virgin GAC was used because exhausted GAC does not have the mechanical properties (i.e., effective size or uniformity coefficient) described in Table 2-2. Before starting up the pilot study, virgin GAC was washed in five-gallon buckets to reduce fines and pH prior to loading media into the pilot columns.

Table 2-2. Filter Media Profile Values					
Media type	Depth (in.)	Effective size (mm)	Uniformity coefficient	Specific gravity	L/d ratio
Filters 1 and 6 – Anthracite, total media depth of 72 inches					
Anthracite	60	1.3	1.28	1.64	1,170
Sand	12	0.61	1.45	2.65	500
Total	72	--	--	--	1,670
Filter 2 – GAC, total media depth of 60 inches					
GAC, Calgon Filtrasorb 816	48	1.26	1.61	1.39	970
Sand	12	0.53	1.42	2.65	580
Total	60	--	--	--	1,550
Filters 3 and 4 – GAC, total media depth of 72 inches					
GAC, Calgon Filtrasorb 816	60	1.26	1.61	1.39	1,210
Sand	12	0.53	1.42	2.65	580
Total	72	--	--	--	1,790
Filter 5 – Anthracite, total media depth of 60 inches					
Anthracite	48	1.22	1.31	1.64	1,250
Sand	12	0.56	1.43	2.65	540
Total	60	--	--	--	1,790

2.3.2 Filter Backwash Setpoints

Table 2-3 shows the backwash initiation criteria and protocol for the filter operations. If one criterion is reached, a backwash is initiated. Throughout the pilot study, the backwash and air scour sequence and protocol were kept relatively constant. The sequence was established to end the filter-to-waste cycle when the turbidity drops below the desired goal. This goal may be adjusted when additional backwash water is needed. Along with turbidity, head loss, and run time, filters can also be backwashed based on particle counts. During the first 4 months of operations, the filters were not backwashed based on the particle count criteria. The turbidity of the filter-to-waste water was recorded every 5 minutes. Filter-to-waste flows are diverted to the pilot plant waste handling system and not the filtered water/backwash supply tank.

Table 2-3. Current Backwash Initiation Criteria and Operation	
Criterion	Value
Maximum turbidity	0.15 NTU ^a
Maximum head loss	12 ft
Maximum filter run time	96 hours
Parameter	Value
Air scour time and rate	1 minute at 3.50 standard cubic feet per minute (scfm)/sf for GAC filters 1 minute at 4 scfm/sf for anthracite filters
Simultaneous air scour/hydraulic backwash fill level and rate	138 inch fill level at 4 scfm/sf and water at 5 gpm/sf for GAC filters 138 inch fill level at 4 scfm/sf and water at 6 gpm/sf for anthracite filter
Low backwash flow time and rate	5 minutes of water at 10 gpm/sf for GAC filters 5 minutes of water at 13.5 gpm/sf for anthracite filter
High backwash flow time and rate	10 minutes of water at 22 gpm/sf for GAC filters 10 minutes of water at 29.25 gpm/sf for anthracite filters
Low backwash flow time and rate	5 minutes of water at 10 gpm/sf for GAC filters 5 minutes of water at 13.5 gpm/sf for anthracite filter
Quiescent settling time	10 minutes
Filter-to-waste	Minimum filter-to-waste timing of 5 minutes, and until filtrate turbidity is ≤ 0.15 NTU

a. UFRVs will be evaluated using truncated data based on 0.1 NTU and PSW, although the backwash trigger has been set at 0.15 NTU to facilitate additional data collection. Maximum turbidity was 0.2 NTU during initial start-up phase.

Air scour and backwash rates were adjusted slightly as needed to achieve the desired 30 percent bed expansion at the high backwash flow stage and bed fluidization at the low backwash flow stage. In addition, due to increased clean bed head loss over time, air scour times and high backwash rates were increased to sufficiently clean the beds regularly. Backwash followed by the start of a filtration run was designed so that it can be completely automated to allow for continuous operation. Note, this pilot study was not intended to focus on backwash optimization.

2.4 Discharge and Solids Handling

The primary waste streams from the pilot facility are settled solids from the sedimentation process, overflow from the flocculation and/or ozone process, overflow from the filter backwash tank, and the filter backwash water, all of which are routed through a solids handling system prior to discharge to an

existing stormwater National Pollutant Discharge Elimination System (NPDES) outfall. The lab module (lab sink) within the pilot enclosure also generates a periodic waste stream, treated by the solids handling system. Waste streams managed by the solids handling system will contain solids from the raw water including natural organic matter, suspended solids, microorganisms, organic and inorganic constituents, as well as small amounts of coagulant metal hydroxides and polymers from treatment chemicals. The waste stream may also include low levels of chlorine residual when chlorine is tested as a pre-oxidant.

The solids handling system includes a gravity fed buried sump (i.e. an equalization basin) from which waste streams from the Intuitech enclosures are pumped to a large settling basin. A 16,000-gallon “Flip Top Weir” tank with dimensions 43-feet x 8-feet x 10.5-feet is used for the settling basin, rented from Rain For Rent (Figure 2-5).



Figure 2-5. Rain For Rent settling basin tank at the pilot plant

16,000-gallon flip top weir tank hydraulic capacity based on 4-inch outlet location

When necessary, solids will be removed as a liquid sludge (estimated to be approximately 2–3 percent by compaction) by a vactor truck for disposal. Solids have not accumulated enough to require a pump out as of December 2019. Decant liquid flows from a 4-inch outlet on the side of the settling tank that is plumbed to discharge to the river through a stormwater NPDES discharge location. The requirements surrounding this discharge process are described below in Section 2.7. A detailed evaluation of recycling will not be conducted for this pilot study.

2.5 Varying Operational Parameters

The treatment chemicals used directly in the pilot treatment process are all NSF-60 approved for potable water consumption and are used at doses below the NSF-60 potable water maximum use level (MUL). Testing reagents, like *N,N* Diethyl-1, 4 Phenyl^oenediamine Sulfate (DPD) for free chlorine testing, are disposed of through the Headworks Facility United Site Services waste removal contract. Prior to disposing of pilot waste, the pH is measured and adjusted if necessary, to be within the following limit: pH to range between 5.0 and 11.5.

Table 2-4 lists the range of these key process parameters tested during the first four months of the pilot study.

Table 2-4. Pilot Plant Unit Process Variables from July to October 2019 of Operations

Variable parameter	Type or units	Variable range
Total raw water flow	gpm	20
Ozonation		
Influent flow per train	gpm	8.5-9.5
Number of basin(s) operating	each	5
Ozone contact detention time ^a	minutes	13.7-15.3
Ozone dose ^a	mg/L	0–1.0
Rapid Mix		
Alkalinity dose	mg/L	0 – 3.0
Number of basin(s) operating	each	3
Detention time	seconds	15.8 -17.6
Velocity gradient (each)	seconds-1	380
Coagulant type	e.g., Alum, Ferric, PACl, ACH ^b	Alum, Ferric, PACl, ACH ^b
Coagulant dose	mg/L	1.5 - 7
Coagulant Aid (Polymer) type	Cationic	Clarifloc C-359
Coagulant Aid (Polymer) dose	mg/L	0 – 1.9
Flocculation		
Influent water flow per train	gpm	8.5- 9.5
Number of basin(s) operating	each	3
Detention time	minutes	30 - 33.5
Velocity gradient (each, tapered)	seconds ⁻¹	25–130
Sedimentation		
Influent water flow per train	gpm	8.5 – 9.5
Detention time	minute(s)	22.1 – 24.7
Settling plates	number	16
Nominal SOR	gpm/sf	1.84 - 2.06
SLR with plates	gpm/sf	0.29-0.32
Sludge flow rate	gpm	0.5
Filtration		
Influent water flow	gpm	8.6–12.6
Filter aid type	Nonionic	Clarifloc N-6310
Filter aid dose	mg/L	0-0.05
Filter 1: anthracite, 72 inches ^a	Loading Rate in gpm/sf	8–12
	Contact Time in min	3.1-4.7
Filter 2: GAC, 60 inches ^a	gpm/sf	6–8
	min	3.1-5.0
Filter 3: GAC, 72 inches ^a	gpm/sf	8–12
	min	3.1-4.7
Filter 4: GAC, 72 inches ^a	gpm/sf	8-12
	min	3.1-4.7
Filter 5: anthracite, 60 inches ^a	gpm/sf	6–8

Table 2-4. Pilot Plant Unit Process Variables from July to October 2019 of Operations

Variable parameter	Type or units	Variable range
	min	3.7-5.0
Filter 6: anthracite, 72 inches ^a	gpm/sf	8-12
	min	3.1-4.7

a. Most vital parameters for detailed design

b. Coagulants include the following: Hydrated aluminum sulfate (alum), polyaluminum chloride (PACl), ferric chloride (Ferric), aluminum chlorohydrate (ACH)

2.6 Water Quality Data Collection

To assess pilot unit operation, staff collected water quality data throughout the study at varying frequencies depending on the parameter. Some parameters are collected to compare against operational goals and performance benchmarks, while others are for process control only.

2.6.1 Comprehensive Water Quality Sampling

During continuous pilot operations from July to October, sampling for a variety of water quality parameters was conducted at different frequencies. Table 2-5 below summarizes the parameters measured and the frequency. All sampling was conducted according to a unique Standard Operating Procedure (SOP) developed by BC and PWB. Sample filtering for true color, filtered ultraviolet absorbance at the 254 nm wavelength (UV₂₅₄), and dissolved organic carbon was performed using polyethersulfone (PES) 0.45 micron filters using either a vacuum or syringe apparatus.

Table 2-5. Comprehensive Water Quality Parameters and Frequency

Parameter	Typical Frequency	Instrument	Method	MRL (method reporting limit)
pH	5x/week	Hach PHC281	SM 4500-H+B	--
Dissolved oxygen (DO)	5x/week	Hach PHC281	Hach 10360	0.10 mg/L
Alkalinity	5x/week	16900 Digital Titrator	Hach 8203	10 mg/L as calcium carbonate (CaCO ₃)
True Color	5x/week	Hach DR3900	Hach 8025	3 color units (Pt-Co)
Apparent Color	5x/week	Hach DR3900	Hach 8025	3 color units (Pt-Co)
Turbidity	5x/week	Hach TU5200	Hach 10258	0.0001 NTU
UV ₂₅₄	5x/week	RealTech UV254 P200 Meter	EPA 415.3	0.0045 ultraviolet absorbance (UVA)
Dissolved UV ₂₅₄	5x/week	RealTech UV254 P200 Meter	EPA 415.3	0.0045 UVA
TOC	3x/week	Shimadzu TOC-V WP	SM 5310C	0.30 mg/L
Dissolved Organic Carbon (DOC)	3x/week	Shimadzu TOC-V WP	SM 5310C	0.30 mg/L
Fe	3x/week	ICPMS	EPA 200.8	5 µg/L
Al	3x/week	ICPMS	EPA 200.8	2-8.1 µg/L
Mn	3x/week	ICPMS	EPA 200.8	0.5 µg/L
Aqueous ATP (Adenosine Triphosphate)	2x/month	PhotonMaster Luminometer	--	0.2 g ATP/mL
AOC, Carboxylic Acids	2x/month	High performance liquid chromatography (HPLC)/ultraviolet (UV)	SM 9217B	0.5-4 ug/L
Media ATP	Seasonally	PhotonMaster Luminometer	--	100 pg ATP/g

2.6.2 Sampling Locations

Sample locations for process monitoring were established between each unit process in order to isolate and evaluate each process. Samples were routinely collected from the following locations:

- Raw water inlet
- Oxidation contact chamber outlet
- Flocculation outlet
- Settled water outlet
- Filter trains 1 and 2 inlet (ozone outlet when operating in intermediate ozonation mode)
- Filter effluent (1, 2, 3, 4, 5, 6)
- Sedimentation sludge drain
- Backwash supply outlet
- Filter sample ports along filter bed column

2.6.3 Online Instrumentation

Turbidity, particle counts, head loss, and pH are continuously recorded by online analyzers. A streaming current monitor (SCM) also assists with process optimization. A trial of the SCM was initially investigated and permanently installed in October 2019.

2.6.3.1 Turbidimeters

HF Scientific MicroTOL turbidimeters (model 28052) are located at the flocculation basin inlets and settled water outlets for each train, and at the filter effluent for each filter. The turbidimeters are calibrated monthly. In addition, weekly verifications are conducted to confirm the calibration is still accurate. If the verification fails, the turbidimeters are recalibrated. Cleaning is also an important component of the turbidimeter operation. Initially the meters were cleaned when needed, and after several weeks of operation the frequency was increased to twice per week to control drift.

2.6.3.2 Particle Counters

Chemtrac Model PC6 particle counters are located on Floc/Sed 1000 influent and effluent, as well as on the effluent of each filter column. The following nine size ranges are set for each particle counter:

- 2 to 3 μm
- 3 to 5 μm (*Cryptosporidium* oocysts diameter)
- 5 to 7 μm (*Cryptosporidium* oocysts and *Giardia* cysts diameter)
- 7 to 10 μm (*Giardia* cysts diameter)
- 10 to 15 μm (*Giardia* cysts diameter)
- 15 to 20 μm
- 20 to 30 μm
- 30 to 100 μm
- $\geq 100 \mu\text{m}$

2.6.3.3 pH Probes

Thermo Scientific AquaSensors DataStick pH probes monitor pH at the flocculation basin inlet and outlet, settled water outlet, and ozone module effluent of each train, at each filter effluent. The pH probes are calibrated and verified monthly. In addition, weekly verifications are conducted to confirm the calibration is still accurate. If the verification fails, the probes are recalibrated.

2.7 Discharge Compliance and Mitigation of Risk to Aquatic Life

The pilot treatment process has a designated discharge of filtered water and effluent from the solids handling system. In order to comply with the NPDES requirements on the permitted outfall, the pilot discharge is required to meet the following limits:

- Total chlorine residual not to exceed 0.1 mg/L
- pH to range between 6.0 and 9.0

Along with NPDES permit discharge requirements, more stringent monitoring requirements were developed alongside PWB's Aquatic Life Supervisors in order to mitigate risk to downstream aquatic life. Dose limits were established for the treatment chemicals based on a safety factor to be significantly below the aquatic toxicity for each chemical. The aquatic toxicity was determined based on the reported

LC50, the lethal concentration considered to result in the death of half of the test population after 96 hours of exposure for fish and 48 hours for invertebrates. Minimum chronic toxicity was also checked for the chemicals with an established criteria available. A goal of maintaining DO levels above 5.0 mg/L was set and a visual inspection and notification protocol for daily monitoring of fish mortality was completed.

Visual inspections of the river for fish mortality and sample analysis of chlorine residual, pH, and DO are completed daily when the pilot is operating. The discharge requirements specific to NPDES are reported monthly to meet the monitoring requirements of the permit. Since the start of operations, the discharge has been within the requirements.

Chapter 3

Raw Water Characteristics

Raw water characteristics from July through October 2019 are summarized in the following chapter presenting monthly averages to understand seasonal variation from the summer to fall season. Table 3-1 below summarizes the average monthly pilot raw water quality during the reporting period from July 1 to October 31 including turbidity, temperature, alkalinity, pH, total particle counts, TOC, DOC, filtered UV₂₅₄, and specific UV absorbance (SUVA). A time series of raw water quality data for key parameters are also presented for the same period in Figure 3-1 through Figure 3-4 below for temperature, alkalinity, pH, TOC, filtered UV₂₅₄, and turbidity, respectively. In addition, Figure 3-5 and Figure 3-6 include algal density and algae genera sampled at the intake during the testing period, followed by Figure 3-7, which shows particle counts in the floc sed inlet.

July through September is classified as the summer season, while October through December is considered the fall season. Water temperature was consistent in the first two months of operation, and then increased 2 degrees in September to an average of 16.1°C (60.3°F). The temperature then decreased steadily by about 3 degrees to an average of 13.5°C (56.3°F) by mid-October (Figure 3-1). In addition, the impact on temperature during a period with intermittent operation was observed, indicating there was a temporary temperature increase in the raw water when the plant was operated intermittently from August 12 to 16, and August 19 to 20, associated with the start-up of the ozone system.

Alkalinity increased over the study period from 8.8 to 12.0 mg/L CaCO₃, while pH stayed about the same through the time period, with an average range from 6.9 to 7.5 (Figure 3-2). TOC was consistent through the summer months (0.73 to 0.78 mg/L), followed by an average increase to 0.95 mg/L with the start of fall, corresponding to the presence of more organics from leaf litter in the reservoirs (Figure 3-3). DOC increased in the same trend, with slightly higher averages from 0.75 to 1.06 mg/L. DOC values were on average greater than TOC as a result of interference from filtering the sample. Filtered UV₂₅₄ was fairly consistent over the reporting period, with a slight increase in October from the summer months from 0.03 to 0.04 cm⁻¹ (Figure 3-3).

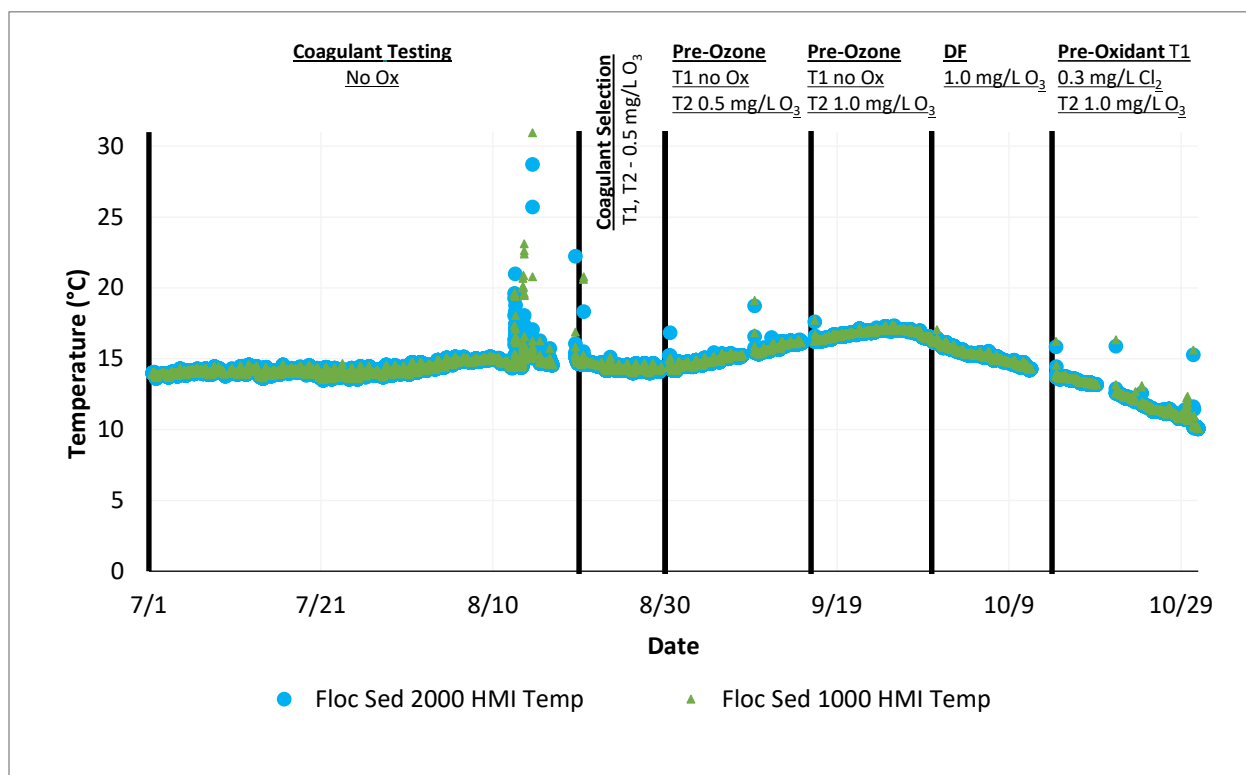


Figure 3-1. Influent temperature from July 1–October 31

A temporary temperature increase occurred from 8/12-8/16 and 8/19-8/20 when the plant was operated intermittently. Condition break lines at 8/20, 8/30, 9/16, 9/30, and 10/14 indicate when the pre-treatment regime changed in a downstream process. Abbreviations: T1 = Train 1, T2 = Train 2, Ox = Oxidant

Table 3-1. Monthly Average Pilot Raw Water Quality (July 1 to October 31)

Month	Temperature (°C) ^a	Alkalinity (mg/L CaCO ₃) ^b	pH ^b	TOC (mg/L) ^{b, c}	DOC (mg/L) ^{b, c}	Filtered UV ₂₅₄ (cm ⁻¹) ^b	SUVA (L/mg-m) ^d	Pilot Inlet Turbidity (NTU) ^e	Headworks Compliance Turbidity (NTU) ^f	Total Particle Counts (#/mL) ^g
July	14.1	8.8	6.9	0.73	0.75	0.03	3.7	0.3	0.2	2,486
August	14.7	9.1	7.3	0.77	0.88	0.03	3.9	0.4	0.3	2,516
September	16.1	11.3	7.5	0.78	0.88	0.03	3.6	0.4	0.4	3,779
October	13.5	12.0	7.4	0.95	1.06	0.04	3.7	0.5	0.4	3,228

a. Monthly average from combination of Floc Sed 1000 Inlet and Floc Sed 2000 Inlet HMI measurements.

b. Monthly average of grab samples collected at the pilot inlet (sampling point FILP-RI-PLT).

c. DOC values are on average greater than TOC as a result of interference from filtering the sample.

d. $SUVA = \text{Filtered UV}_{254} / \text{DOC} * 100$

e. Monthly average of grab samples for turbidity collected at the combined pilot inlet upstream of the flow split to the two floc sed trains.

f. Monthly average of compliance turbidity measurements recorded every 4 hours at headworks raw water inlet.

g. Total particle counts include combination of particles in all bin sizes (2-100 µm). Note, the particle counters are located after the ozone unit on Floc Sed 1000, and represent pre-treated raw water when a pre-oxidant was dosed (ozone or chlorine).

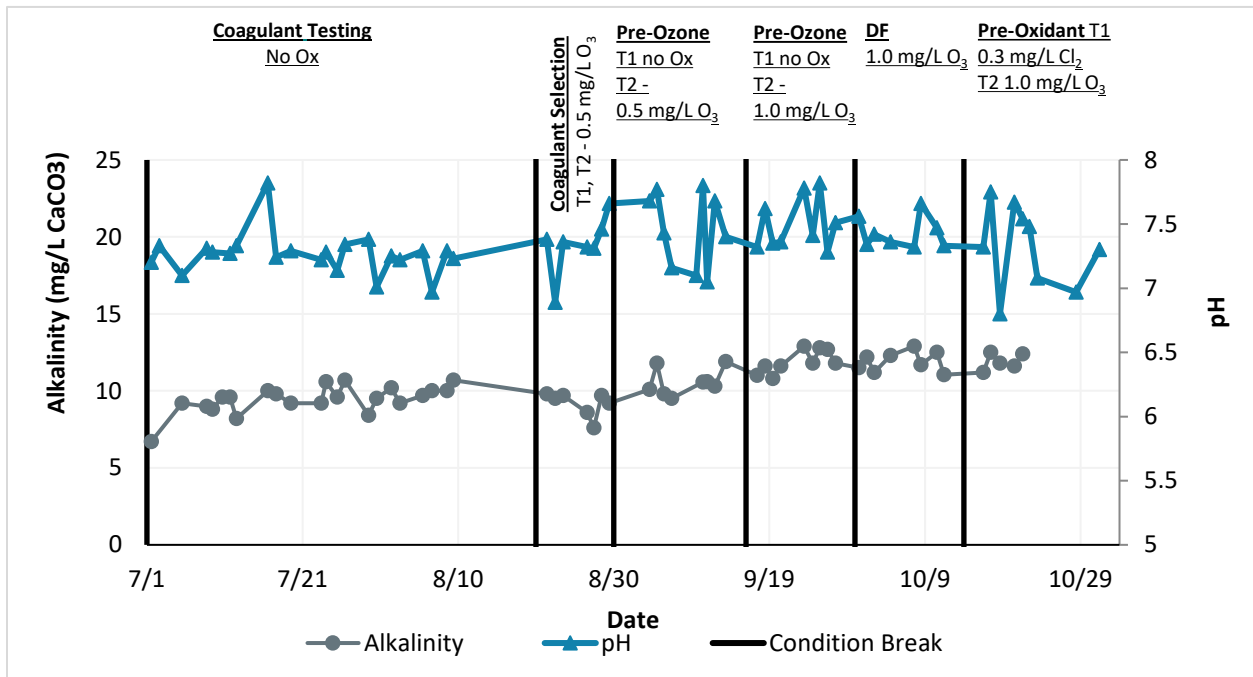


Figure 3-2. Influent alkalinity (left axis) and pH (right axis) from July 1–October 31

Condition break lines at 8/20, 8/30, 9/16, 9/30, and 10/14 indicate when the pre-treatment regime changed in a downstream process. Abbreviations: T1 = Train 1, T2 = Train 2, Ox = Oxidant

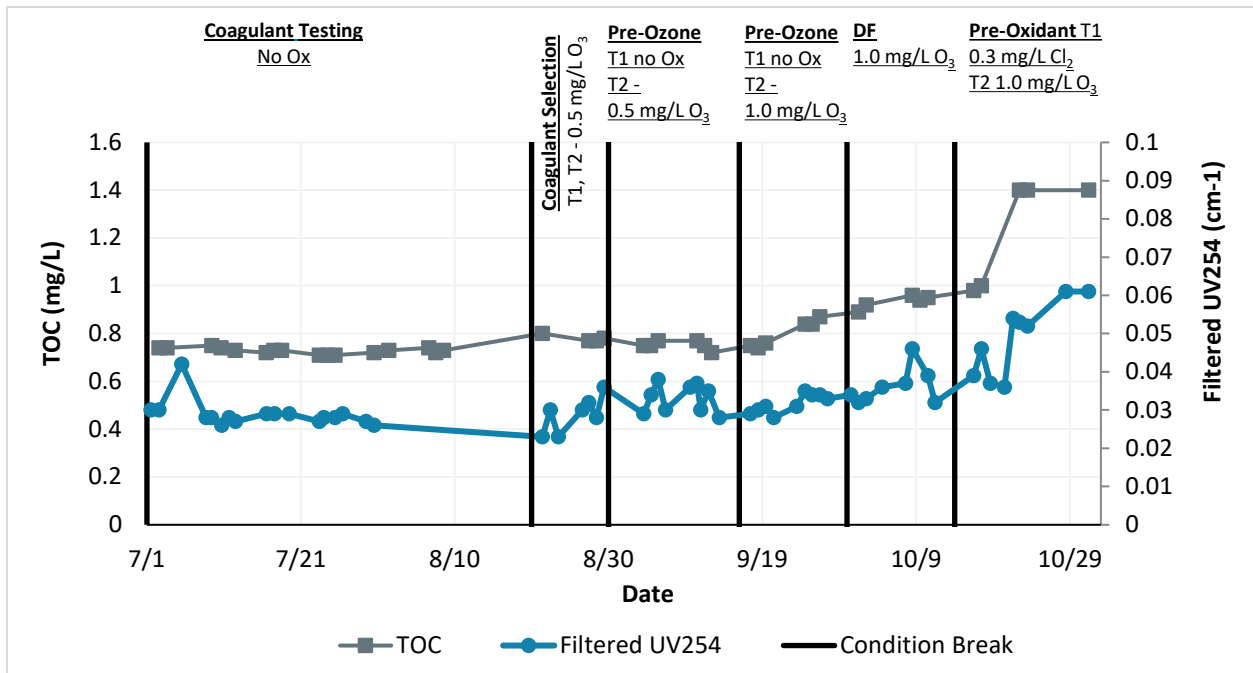


Figure 3-3. Influent TOC (left axis) and filtered UV₂₅₄ (right axis) from July 1–October 31.

Condition break lines at 8/20, 8/30, 9/16, 9/30, and 10/14 indicate when the pre-treatment regime changed in a downstream process. Abbreviations: T1 = Train 1, T2 = Train 2, Ox = Oxidant

3.1 Raw Water Turbidity

Raw water turbidity data are presented in Figure 3-4, showing the data from online turbidimeters to the pilot Train 2 (Floc Sed 2000 HMI) recorded at a five-minute interval along with grab sample data collected daily during the week, as well as turbidity measurements from the compliance samplers at the headworks raw water inlet recorded every four hours. The grab samples, which are collected at the combined inlet before the influent flow is split, overlap the compliance samples throughout most of the testing period. The grab samples gradually increased over time from an average of 0.3 NTU in July to an average of 0.5 NTU in October, as expected based on historic seasonal variation with increased turbidity in the summer to fall season.

There is consistently more scatter in the pilot inlet turbidimeters than the compliance and grab samples. The scatter is related to the shorter measurement frequency of five minutes for the online turbidimeters, which reflects minor temporary fluctuations when the meters are calibrated or there is an interference from material build-up on the meters, as well as analytical limitations of the turbidimeters. While there is more scatter in the pilot inlet turbidimeters, the measurements generally aligned with the compliance and grab samples. To reduce scatter and limit analytical error, the Floc Sed inlet turbidimeters are calibrated monthly, along with a weekly verification process to check the readings compared to a bench-top turbidity measurement. In addition, a more frequent cleaning cycle was initiated to avoid interference due to material build-up and to control drift.

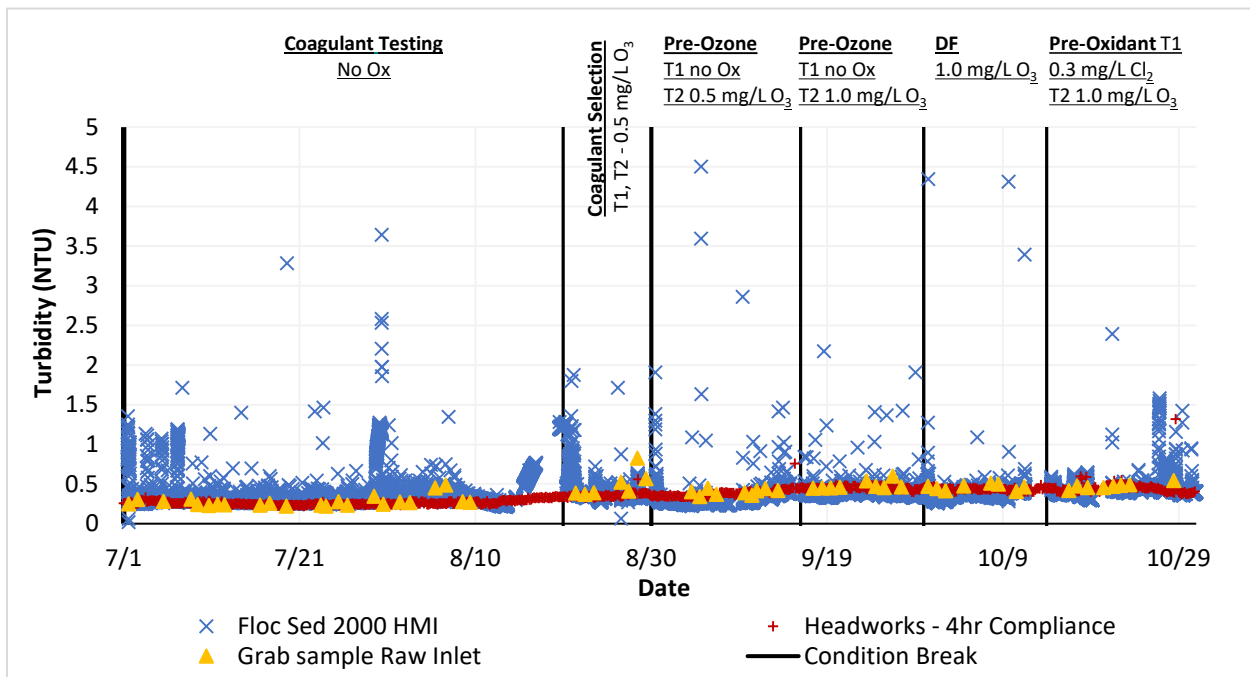


Figure 3-4. Raw water turbidity levels in the pilot trains from July 1 – October 31

Condition break lines at 8/20, 8/30, 9/16, 9/30, and 10/14 indicate when the pre-treatment regime changed in a downstream process. Abbreviations: T1 = Train 1, T2 = Train 2, Ox = Oxidant

3.2 Algae Levels in Raw Water

Algal density in units/mL sampled weekly from July 1 to October 31 at the Headworks intake, located upstream of the pilot plant, are presented in Figure 3-5. Algal densities ranged from 610 units/mL in mid-July to a high of 1,400 units/mL in late-October. There were two samples that were above the PWB threshold for phytoplankton (1,200 units/mL) during the time period, including a high of 1,200 units/mL on September 16, and 1,400 units/mL on October 21. Almost all of the five algae genera with the highest levels observed during the testing period had algal densities below 500 units/mL, and typically under 100 units/mL (Figure 3-6). Of the five phytoplankton with maximum densities measured during the testing period, *Melosira* and *Dinobryon* are known filter cloggers, and *Chlamydomonas* and *Mallomonas* can cause taste and odor. The average densities observed for those four types was between 43 and 160 units/mL. During the testing period, there were a few cyanobacterial genera (*Aphanocapsa*, *Aphanothece*, and *Coelosphaerium*) with maximum densities between 55 and 77 units/mL, but none are known cyanotoxin producers.

During this time period, there were no reported issues with filter operation directly correlated to algae in the intake. Algal densities at the intake will continued to be monitored throughout the remainder of the study.

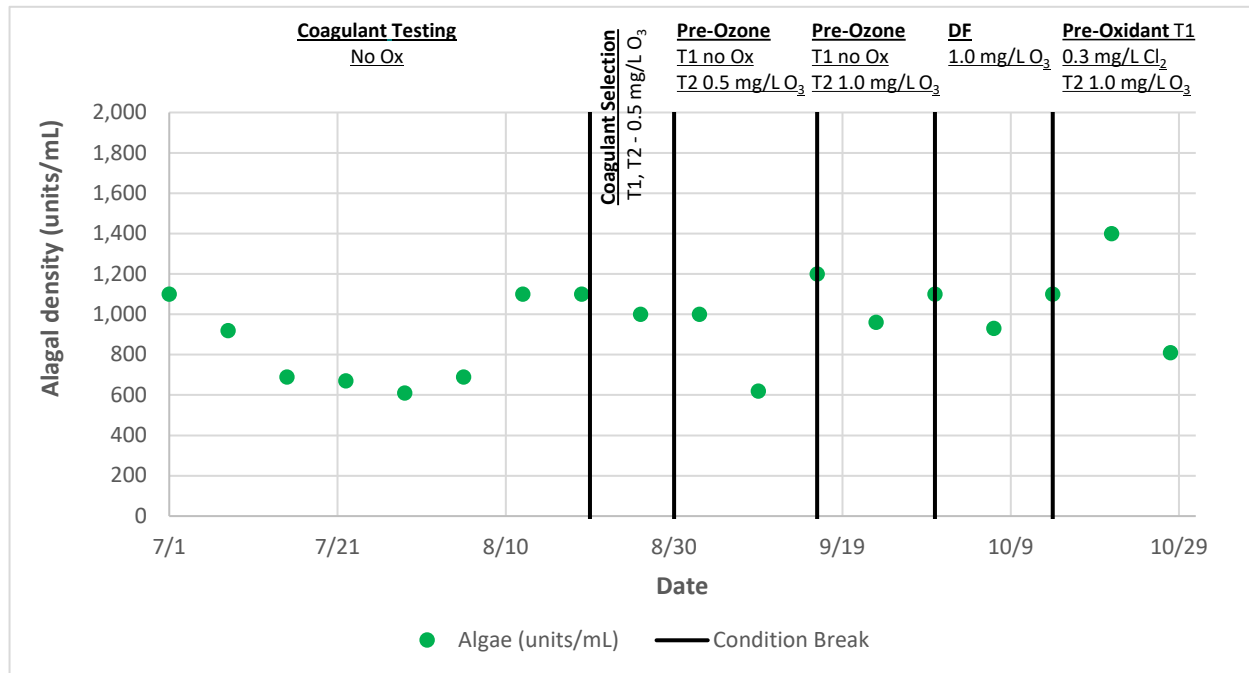


Figure 3-5. Total algal density in the intake from July 31–October 31

Condition break lines at 8/20, 8/30, 9/16, 9/30, and 10/14 indicate when the pre-treatment regime changed in a downstream process. Abbreviations: T1 = Train 1, T2 = Train 2, Ox = Oxidant

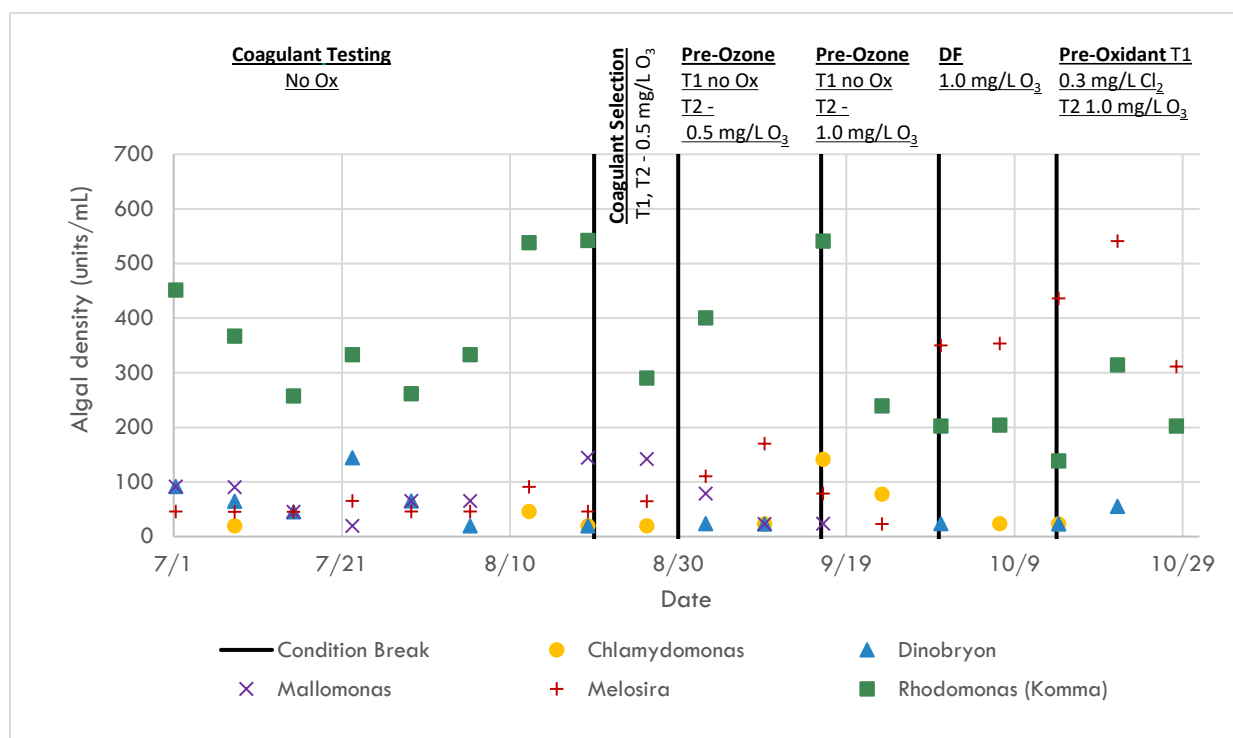


Figure 3-6. Algal density for the five genera with the maximum densities sampled from July 1 to October 31

Condition break lines at 8/20, 8/30, 9/16, 9/30, and 10/14 indicate when the pre-treatment regime changed in a downstream process. Abbreviations: T1 = Train 1, T2 = Train 2, Ox = Oxidant

3.3 Floc Sed Inlet Particle Counts

Particle counts from the Floc Sed 1000 inlet (Train 1) are presented in Figure 3-7. This sample location is the furthest sample point upstream in the process where particle counts are collected; however, it does not represent a true raw water when pre-oxidation is active, because it is downstream of the pre-oxidation pilot module. When pre-oxidation is active, the recorded particle counts may differ from the particle count distribution in the raw water, which would change the log removal calculations and possibly lead to underestimation of total log removal from raw water.

During this time period, there were three pre-treatment conditions applied to Train 1. Pre-treatment consisted of a period with pre-ozonation at a dose of 0.5 mg/L from August 20–30, an increased ozone dose of 1.0 mg/L from September 29–October 11, followed by a period with pre-chlorination at a dose of 0.3 mg/L Cl_2 . The particle counters were unreliable during the first month of operations from July 1–July 31, and therefore these data were excluded from the dataset. In addition, two time periods, August 25–29 and September 13–14 had repeat values because of a communication issue with the HMI and were also excluded.

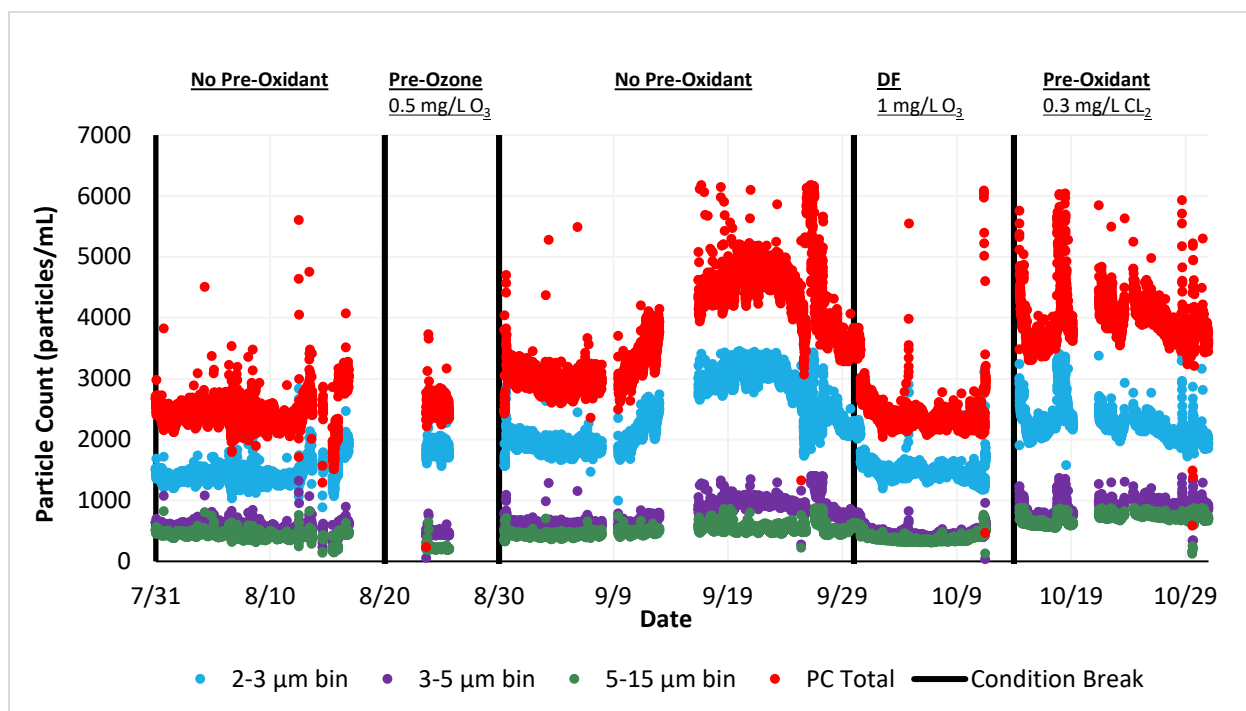


Figure 3-7. Particle counts at the Floc Sed 1000 inlet (Train 1) intake from July 31–October 31

Counts for 2-3 µm, 3-5 µm, and 5-15 µm bin sizes and the total count for all bin sizes. Data from 7/1–7/29 are unreliable and were excluded. Condition break lines at 8/20, 8/30, 9/16, 9/30, and 10/14 indicate when the pre-treatment regime changed in Train 1.

For the month of August, the total particle counts in the raw water were on average 2,500 particles/mL. The total particle counts increased consistently after August 30. The increase was almost entirely in the 2–3 µm bin. Particle counts steadily increased from about September 10 to a high around September 20 after which counts decreased to levels observed in July. The increase in particle counts in mid-September corresponds to when an increase in algae counts from about 600 units/mL to 1,200 units/mL in the intake were measured (Figure 3-5). The reduction in particle counts in early October could be partially a result of pre-ozonation at a dose of 1.0 mg/L O_3 exhibited by the timing of the reduction and start of the pre-ozone trial. Ozone was stopped and switched to a pre-chlorination condition at a dose of 0.3 mg/L Cl_2 , at which time the total particle counts increased again back to levels similar to before ozone was dosed. This observation suggests there was a correlation in the change to particle counts and the ozone treatment. Based on this observation, pre-ozonation will be applied primarily to Train 2, to limit effects by ozone on the intake particle counts. The pilot team is also investigating moving the sample location to collect a true raw water sample.

The average counts in the 3 to 5 µm bin were between 557 to 765 particles/mL during the reporting period, indicating that the raw water has a low number of particles similar in size to *Cryptosporidium*. Particle counts in the 5 to 15 µm range, which is the size of *Giardia*, were also low, averaging between 402 to 554 particles/mL.

3.4 Summary

Raw water quality parameters for the period of testing described in this report (July through October 2019) are presented in this chapter. As the source water is the Bull Run Reservoir, raw water quality was generally consistent. Temperature ranged from a high of 16.1°C in September to a low of 13.5°C by mid-October. Alkalinity increased over the test period from an initial value of 8.8 mg/L as CaCO₃ in July to 12 mg/L as CaCO₃ in October while pH was generally consistent, ranging from 6.9 to 7.5 over the test period.

Pilot raw water turbidity was consistently low, ranging from 0.3 NTU in the summer months and increasing to an average of 0.5 NTU by the end of October with Headworks turbidity slightly lower at 0.2 NTU in the summer months and 0.4 NTU by the end of October. Algal densities ranged from 610 units/mL in mid-July to a high of 1,400 units/mL in late-October. Particle counts were also generally low during the test period. While the total particle count ranged as high as 5,000 to 6,000 counts/mL in September, the average counts in the size ranges serving as surrogates for pathogens were relatively low. Particles in the 3 to 5 µm bin were between 557 to 765 counts/mL during the reporting period, indicating that the raw water has a low number of particles similar in size to *Cryptosporidium*. Particle counts in the 5 to 15 µm range, which is the size of *Giardia*, were also low, averaging between 402 to 554 particles/mL.

Chapter 4

Pilot Study Results

The following section discusses the bench-scale and pilot-scale testing completed during the first four months of pilot plant operations, including for the following scenarios tested with the dual pilot treatment trains (Table 4-1):

Table 4-1. Summary of testing scenarios for pilot plant study from July 1 to October 31

Test Duration	Testing Scenario	Conditions
July 1 to August 30	Coagulant testing of alum, ferric chloride, PACl, and ACH over two months	Tested various chemical dosages of coagulants, coagulant aid, and filter aid.
August 30 to September 29	Pre-oxidant testing with pre-ozonation vs. no pre-oxidation for one month	Dose of 0.5 mg/L ozone (O ₃) followed by a period with an increased ozone dose of 1.0 mg/L O ₃ . PACl with filter aid and no coagulant aid for both trains.
September 30 to October 11	DF testing with pre-ozonation for two weeks	DF vs. conventional treatment with pre-ozonation dose of 1.0mg/L O ₃ , PACl with filter aid and no coagulant aid for both trains.
October 14 to 21	Pre-chlorination testing with pre-chlorine vs. pre-ozonation over one week	Chlorine dose of 0.3 mg/L Cl ₂ and ozone dose of 1.0 mg/L O ₃ . PACl with filter aid and no coagulant aid for both trains.
July 1 to October 31	Filter Design	Filter loading rates and media type with various pre-treatment conditions.

4.1 Filter Operation

Throughout the testing period, the filters were operated with the media configuration presented in Figure 4-1, indicating the train, filter number, media type, depth, and range of flow rates. The pilot was operated in the filtration rate configuration of 6 and 8 gpm/sf, from the onset of operations through July 26, 2019. Subsequently, filtration rates were increased to the high filtration rate configuration of 8 and 12 gpm/sf for the remainder of the testing duration. Chemical doses that were applied for treatment are specified in the specific results scenario sections below.

4.1.1 Analysis Parameters

Testing scenarios listed above were analyzed for the following parameters:

- UFRVs
- Particle counts
- Organics removal

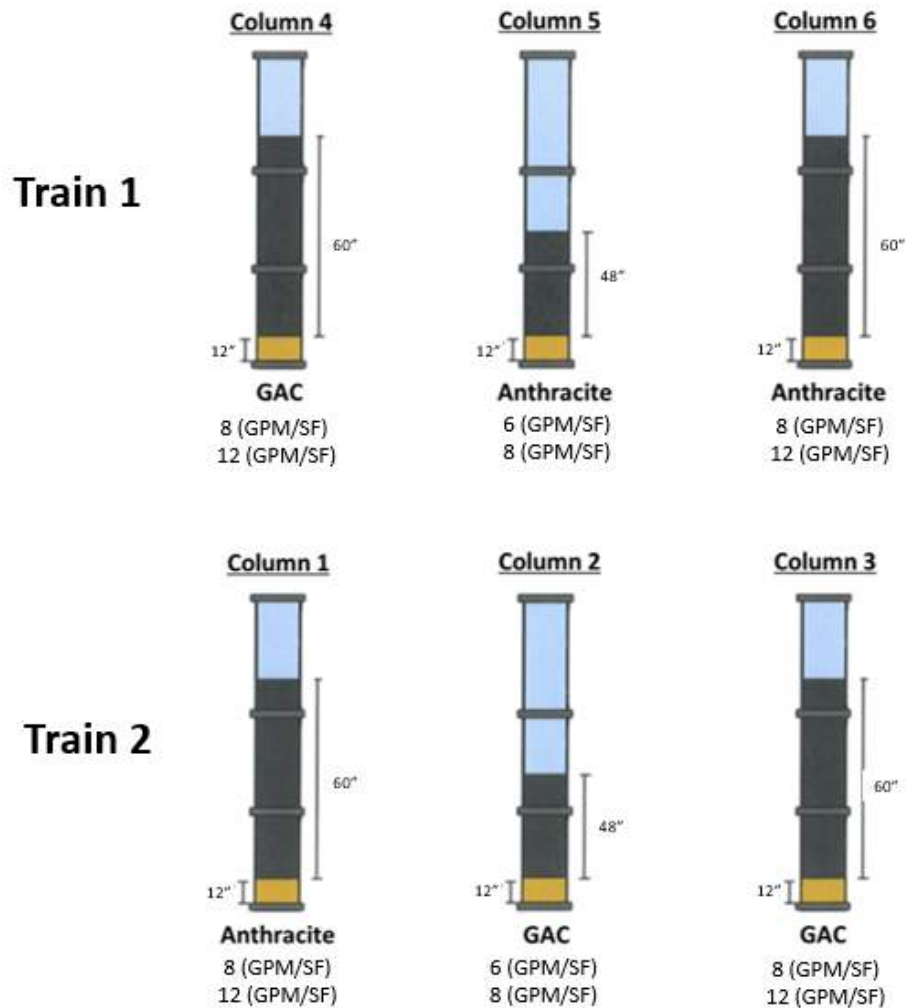


Figure 4-1. Pilot filter arrangement showing the train, filter number, media, depth, and filtration rate

Some general considerations for how the data were evaluated and processed for each parameter are provided below.

4.1.1.1 UFRVs

Filter productivity is assessed using the UFRV metric, which normalizes filter run time with hydraulic loading rate to assess the volume of water treated per unit filter area for a given filter run. UFRV is calculated by multiplying the filtration rate (in gpm) by the filter run time (in minutes) and dividing by the filter area (in sf). Because UFRV normalizes the filter run time by the filtration rate, it can be used to compare performance between filters operated at different loading rates.

Of the three variables used to calculate UFRV (filtration rate, filter run time, and filter area), only one variable is constant between runs due to the design of the pilot equipment: filter area. Filtration rate, one of the other two variables, is set as an independent variable and generally remains constant between multiple runs. Only two filtration rates have been tested, per filter, over the course of the study thus far:

- 8 gpm/sf for Filters 1, 3, 4, and 6; 6 gpm/sf for Filters 2 and 5
- 12 gpm/sf for Filters 1, 3, 4, and 6; 8 gpm/sf for Filters 2 and 5

The last variable, filter run time, is the only dependent variable assessed as part of the UFRV calculations and, as such, will vary between runs in response to other independent variables such as pre-oxidant and flocculation/sedimentation conditions.

For the purpose of this study, a distinction is made between calculated filter run time, based on the period of time during which filter effluent turbidity meets the target filter goals, and physical filter run time, which is the time between filter backwash events. Depending on the filter effluent turbidity, calculated filter run time may match the physical filter run time or be less than the physical filter run time, but it is not possible for the calculated filter run time to exceed the physical filter run time. The physical filter run time ends when the filters backwash, which in turn is triggered when one of the following criteria are met:

- Filter effluent turbidity exceeds trigger level of 0.15 NTU for more than 1 minute (trigger level of 0.20 NTU was used during startup and earlier testing)
- Total head loss through the filter exceeds 12 ft
- Total filter run time exceeds 100 hours (this criterion has not been met during the course of pilot testing to date)

The calculated filter run time is determined algorithmically, based on a lower turbidity level of 0.10 NTU. The algorithm used to calculate filter run time performs two functions:

- It removes the portion of the ripening curve during which filter effluent turbidity is above 0.10 NTU from the beginning of the filter run, and
- It calculates the end of the filter run as occurring when more than five percent of the filter run time is above 0.10 NTU (but less than 0.15 NTU), or when the total filter head loss exceeds 12 ft.

The first criterion excludes data that are collected that occur during the ripening period which, in the full-scale plant, would correspond with a filter-to-waste operation. The second criterion is based on the PSW goal of keeping 95 percent of individual filter effluent turbidity values at or below 0.10 NTU. These criteria are presented graphically for a typical filter run (Figure 4-2).

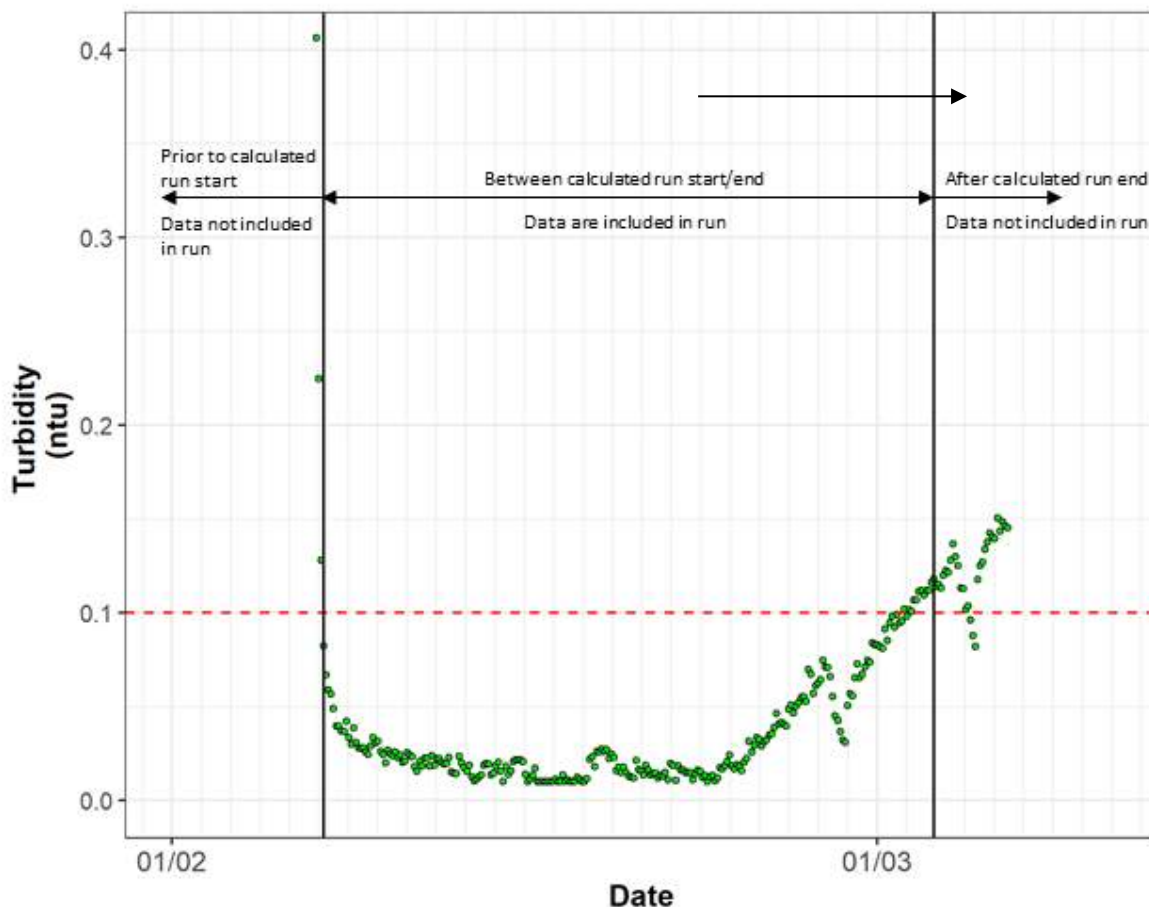


Figure 4-2. Example of data used when calculating filter run time

Data evaluated in this report have been analyzed in the context of individual filter runs (i.e., data collected outside of a calculated filter run have not been analyzed). Filter runs have been reviewed for data completeness, and data from runs that were terminated prematurely (e.g. due to manual backwash or power loss) have been censored from the data set. Similarly, filter runs where filter effluent turbidity did not fall below 0.10 NTU (e.g. due to inadequate pre-treatment conditions or instrumentation error) have been censored from the data set.

4.1.1.2 Particle Counts

While UFRV has been calculated based on filter effluent turbidity, filter effluent particle counts have also been monitored and provide another useful metric for filter performance and for use as a surrogate for pathogen removal. As with other filter data, the particle count data have been truncated based on calculated filter runs, and particle count criteria collected during runs that were censored from the UFRV data were similarly censored from the particle count data set.

In addition to the particle counters on each filter, Flocculation/Sedimentation Module 1000 (Floc Sed 1000) has particle counters to measure particle counts in the influent and settled water streams on Train 1. These particle count data, along with the filter effluent particle count data, were also censored if they did not meet the following criteria at the time of collection:

- Measurement cell transmittance ≥ 90 percent

- Sample flow rate within the flow ranges specified below:
 - Flow to filter particle counters between 60 mL/min to 90 mL/min
 - Flow to floc/sed particle counters between 50 mL/min to 80 mL/min

Particle counts were binned into nine discrete particle size ranges over the course of the filter run. For the purposes of this report, the following size ranges will be presented for discussion:

- 3 to 5 μm (surrogate for *Cryptosporidium*)
- 5 to 15 μm (surrogate for *Giardia*)

4.1.1.3 Organics Removal

Organics removal through the treatment process was assessed for the testing scenarios in terms of TOC, true color, and UVA at 254-nm (UV_{254}). DOC, apparent color, and unfiltered UV_{254} data were measured as well and were used or excluded from the analysis for the following reasons:

- DOC was measured for the first four months of operations; however, the results were consistently close to or higher than the TOC values at all locations. This suggests the majority of the TOC in the raw water is in the dissolved form prior to treatment. While it is apparent that some treatment steps change the organic carbon from a dissolved form to a particulate form (e.g. the reduction in DOC relative to TOC during sedimentation indicates that some DOC is adsorbed by the settled floc), many measurements of DOC (particularly in the filter effluent samples that were very close to the analytical method reporting limit) appear to be influenced by analytical interference caused by organics leaching from the filter paper used to prepare the DOC samples for analysis. Because of the analytical variability and consistent interference issue resulting in DOC values greater than TOC, it was concluded that DOC is not an informative parameter for the filter performance, therefore, organics removal is based on TOC for the pilot study. In addition, filtering the sample for DOC measurement of filtered effluent was discontinued for future testing.
- UV_{254} is another surrogate for organics removal. The amount of UV_{254} absorbed is related to the amount of organics present in the sample. UV_{254} and filtered UV_{254} were both measured throughout the testing duration; however, there were short durations when only UV_{254} was sampled. In addition, sampling for filtered UV_{254} for the filtered effluent was discontinued after October 9, due to issues with the sample filter contaminating the sample causing a false increase in the result. Therefore, unfiltered UV_{254} results are presented for filtered effluent for the full duration of the testing period.
- Apparent color is presented from July 1–23 and from October 9–31 in the absence of true color data. Apparent color is unfiltered and may have interference from turbidity that appears as color. Color data that were below the detection limit (3 platinum cobalt [Pt-Co] units) were replaced with half the detection limit (1.5 Pt-Co units).

4.2 Coagulant Testing and Selection

This section describes the bench-scale jar testing conducted in preparation for the pilot testing to inform the initial coagulant selection (Section 4.2.1), followed by detailed results from the coagulant testing and selection at the pilot (Section 4.2.2). Four primary coagulants (alum, ferric chloride, PACl, and ACH) were evaluated during bench- and pilot-scale testing.

The objective of coagulant testing at bench-scale was to see if any coagulants could be eliminated from consideration at pilot-scale. The objective of pilot-scale coagulant testing is to establish a consistent pre-treatment approach that can be used in subsequent testing of other important treatment parameters. It

is not the intent of the bench- or pilot-scale coagulant testing to dictate what pre-treatment approach the full-scale facility will use.

4.2.1 Bench-scale Jar Testing

Prior to start-up of the pilot plant testing, PWB, BC, and Confluence staff conducted jar testing to evaluate coagulants and polymers. The bench testing approach was based upon conducting a multi-phased group of jar test runs. Testing evaluated coagulation performance with Bull Run water across three phases of tests by (1) performing a wide-range dose screening of coagulants, (2) evaluating narrowed coagulant dosage ranges that performed the best, (3) evaluating coagulation assisted by cationic polymer(s), nonionic and/or anionic polymer(s). More detailed results for each jar testing round are included in Appendix A.

PWB conducted jar testing in the PWB Lab with inorganic, metal-salt coagulants, and some select polymer blends, including the following:

- Alum
- Ferric chloride (PIX-311)
- Polyaluminum chloride, (PACl, PAX-18)
- Aluminum chlorohydrate (ACH)
- Clarifloc C-3226 (Coagulant aid cationic polymer)
- Praestol 851TR (Coagulant aid cationic polymer)
- Praestol 650TR (Coagulant aid cationic polymer)
- Praestol 3040LTR (Filter aid anionic polymer)
- Praestol 2500 (Filter aid nonionic polymer)

During jar testing, alkalinity was added for coagulant dose conditions for alkalinity-limited conditions, avoiding large fluctuations in pH as a result of adding alum and ferric chloride, which both consume alkalinity when added to water.

The jar testing apparatus used for these experiments was a Phipps and Bird, six-jar, programmable gang-stirrer apparatus with square, 2-liter (L) jars. Mixing using the attached stirrers operated at an equivalent speed across each jar depending on the control panel setting. Sampling was conducted by withdrawal at a slow rate through sample ports (e.g., a low-flow rate that does not disturb floc blankets located below the sample port) at the bottom of each jar.

PWB conducted jar testing on water collected in December 2018, March 2019, and April 2019. The December 2018 water captured raw water with high organics (TOC was 1.5 mg/L) for the source water. Turbidity was 0.35 NTU, and alkalinity was 9.5 mg/L as calcium carbonate (CaCO_3). The March 2019 raw water sample had a turbidity of 0.26 NTU, TOC of 1.0 mg/L, and alkalinity of 7.8 mg/L as CaCO_3 , and the April water was to test turbid water following a storm with raw water turbidity approximately 2 NTU, but that decreased to 0.84 NTU prior to testing. Alkalinity for April water was 5.4 mg/L CaCO_3 and TOC was 2.0 mg/L. Testing on water processed by jar testing included evaluation of the filterability index (FI) on post-settled water. The FI test is a method to compare coagulant types and dosages against each other for their later potential to be filtered. Water quality and other testing were evaluated before and after the FI test. The jar test analysis included evaluations of visual floc appearance and time of initial formation, pH, turbidity, apparent color, true color, alkalinity, UV_{254} (unfiltered and filtered through a 0.45 μm filter), TOC, and DOC.

Visual floc was difficult to obtain in jar testing. Results showed that low coagulant doses have positive results when considering the filterability, decreasing turbidity, and minimizing organic matter.

After the completion of the first round of testing (December 2018), observations included:

- Very low raw water turbidity brought challenges to analyzed results, with improvement difficult to quantify.
- Most coagulants showed good particle removals at both low and high dosages, with some coagulants showing good TOC and DOC removals at the higher dosages.
- The addition of nonionic polymer showed mixed results with the different coagulants. In combination with ACH, lower turbidity and better filterability was obtained but this was not the case for alum and ferric.

During the second round of testing (March 2019), the following results were observed:

- All coagulants performed well with respect to FI time and turbidity at dosages ranging from 3 mg/L through 5 mg/L, depending on the coagulant.
- There was significant removal of DOC, at times a 40–60% reduction, when primary coagulants were dosed at 5 mg/L.

This third round of jar testing (April 2019) continued to show that low coagulant doses have significant potential for pilot testing selection. A summary of findings from the April 2019 jar testing includes the following:

- All coagulants showed relatively good turbidity and filterability performance at ≤ 6 mg/L dose (e.g., good performance was observed at 3 mg/L).
- Ferric testing was not consistent (good turbidity reduction in the first test, poor turbidity reduction in the next test, and poor color removal and ultraviolet transmittance (UVT) conditions at a low dose).
- Excellent reduction in organics was achieved. TOC results (unfiltered samples), show that settling alone removes at least 20% TOC at a dose as low as 3 mg/L for all coagulants. Alum and ferric removed a high level of DOC at doses as low as 6 mg/L. All coagulants removed $>70\%$ DOC at a dose of 9 mg/L.

Jar testing along with a combination of assessments involving the review of specific treatment parameters were completed to determine which coagulants (and polymers) may be useful to evaluate during pilot testing. Based on the assessment of treatment parameters (such as turbidity removal, FI, FI turbidity and filtration time, and reduction in organic matter surrogates such as color, UV_{254} , DOC, and TOC), the results from jar testing were not definitive enough to remove any potential coagulants for investigation during pilot operations. All four coagulants were evaluated via pilot testing.

4.2.2 Pilot Coagulant Selection–Summer/Fall Season

After 3 weeks of initial wet testing, operation with chemical addition began in start-stop mode from June 18–30 with the goal to select chemical dosages to validate during continuous operation. The first week of coagulant testing involved comparing alum and ferric chloride, followed by a week comparing the other two coagulants, PACl and ACH. Data collected during this period were not considered representative because the pilot was operated intermittently, so they are not presented here; however, operations during this period were used to inform chemical dosages used during the subsequent continuous operations.

Full continuous operation of the pilot commenced on July 1. The initial screening period during continuous operations evaluated alum and ACH initially for one week, followed by a week of testing with PACl and ferric. Throughout this initial screening period pH adjustment chemicals were not utilized; the pH during coagulation was only influenced by the raw water pH and the natural impact of the coagulant. Based on initial performance, PACl and alum were selected for a side-by-side comparison for additional evaluation of chemical dosages and combinations with coagulant aid and filter aid. The following section discusses the performance of each coagulant during the initial screening, followed by result from the alum and PACl side-by-side comparison testing.

The particle counters initially provided for the pilot were not properly calibrated. A field calibration of the pilot's particle counters was conducted by Chemtrac on July 31. Particle count data collected prior to that date are considered unreliable and are not presented.

4.2.2.1 Alum – Initial Screening

Coagulant testing was initiated with a comparison of alum and ACH as part of the initial screening. The initial alum dose was chosen based on the three rounds of jar testing performed prior to the pilot testing. The initial alum dose during intermittent operations was set at 3.3 mg/L as alum and was adjusted to 4.2 mg/L. Alum was dosed at 4.2 mg/L from July 1–5, followed by the addition of nonionic filter aid of 0.03 mg/L from July 5–8. During this period, the filters were operated at 8 gpm/sf for the 72-inch column depth filters (Filters 1, 3, 4, and 6) and 6 gpm/sf for the 60-inch column depth filters (Filters 2 and 5).

During this initial screening of coagulants, relatively few runs were collected because of the manner in which the pilot was initially operated during startup. The filters were originally set to backwash based on a 0.20 NTU turbidity threshold, which allowed for extended filter runs collecting data above the 0.10 NTU target. This is best illustrated in Figure 4-3, which compares the turbidity data collected from Filter 6 during the initial screening of alum to the turbidity corresponding to the calculated filter runs (calculated using the procedure outlined in Section 4.1.1).

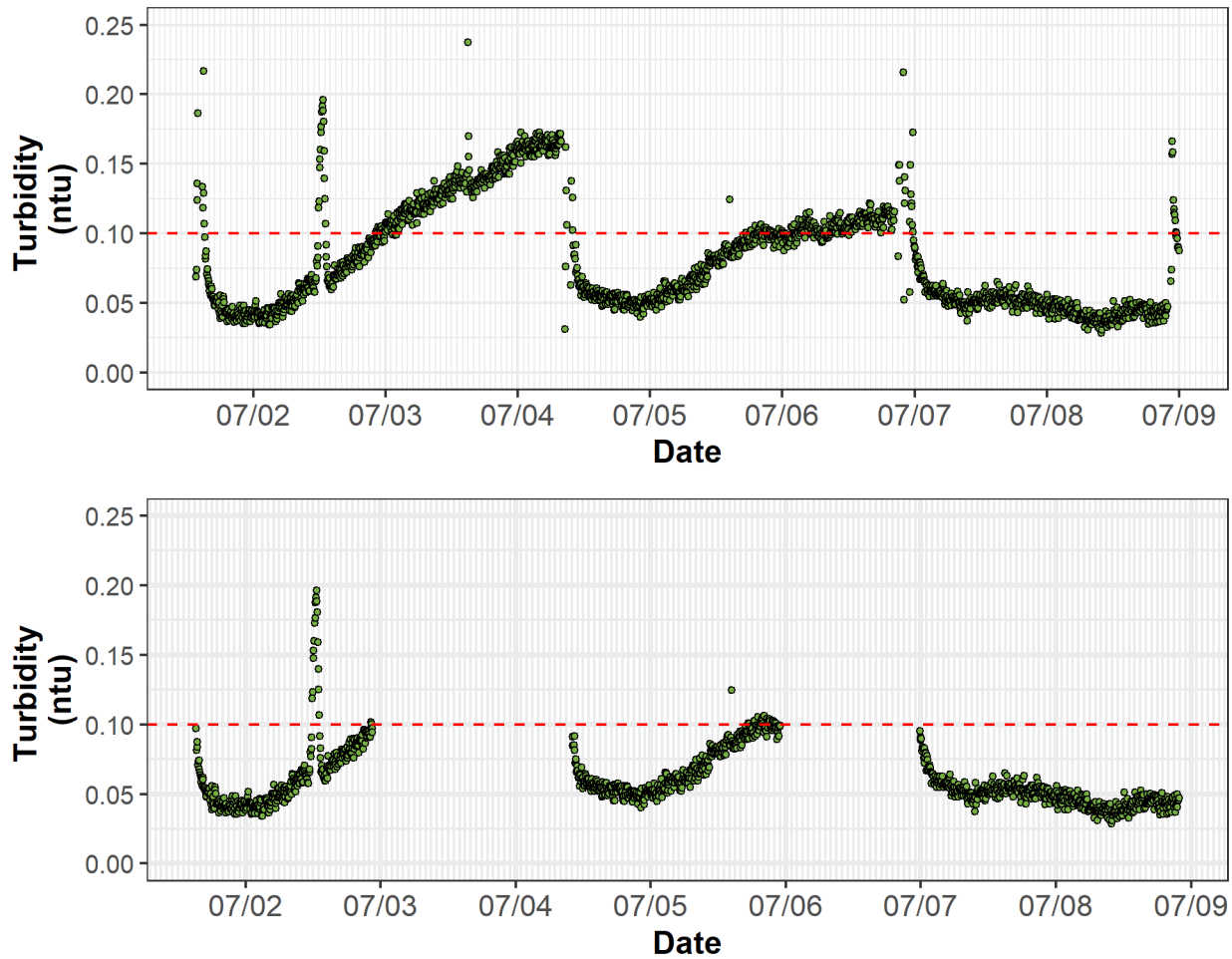


Figure 4-3. Comparison of Filter 6 turbidity data (top) to Filter 6 turbidity data corresponding to calculated filter run times (bottom) during initial alum screening

Relatively few runs were collected during this initial screening period because of extended periods during which filter effluent exceeded 0.10 NTU along with operating at the lower filtration rate. UFRVs for the runs conducted during this period are shown in Figure 4-4.

The format used for Figure 4-4 is consistent with how filter UFRVs will be presented in this report. The x-axis shows the media for each filter, followed by a number representing the filtration rate in gpm/sf. Above the x-axis, the number of runs included in the box and whisker plot is presented. If three or fewer data are included in the data set being plotted, discrete data points are plotted instead of a box and whisker plot. A horizontal dashed red line represents the UFRV goal of 6,500 gallons per square foot (gal/sf) for 95 percent of the operation as specified in the Work Plan (BC 2019), and the horizontal dashed orange line presents a higher performance goal of 10,000 gal/sf.

Box-whisker plots are used throughout this document. The bottom of the box represents the 25th percentile value or first quartile where 25 percent of the data is below this value. The top of the box represents the 75th percentile value or third quartile where 75 percent of the data is below this value. The line in the middle of the box is the median or 50th percentile value. The difference between the first and third quartiles is defined as the interquartile range (IQR). The lines that extend from the box, known as whiskers, represent either the maximum or minimum value recorded, or 1.5 times the IQR if outliers are suspected. Values that are more than 1.5 times the IQR above third quartile or more than 1.5 times

the IQR below the first quartile are suspected outliers. For example, if the maximum recorded value was less than 1.5 times the IQR, the upper whisker would extend to that maximum value. If the maximum value recorded exceeded 1.5 times the IQR, the upper whisker would extend to 1.5 times the IQR above the upper hinge. Values above that would be represented as points in the boxplot and would be considered potential outliers. Similar logic extends to the representation of the lower whisker.

Figure 4-5 summarizes the filter effluent turbidities recorded during the runs that are represented in Figure 4-4. Turbidities recorded during periods that were truncated from the filter run record have not been included.

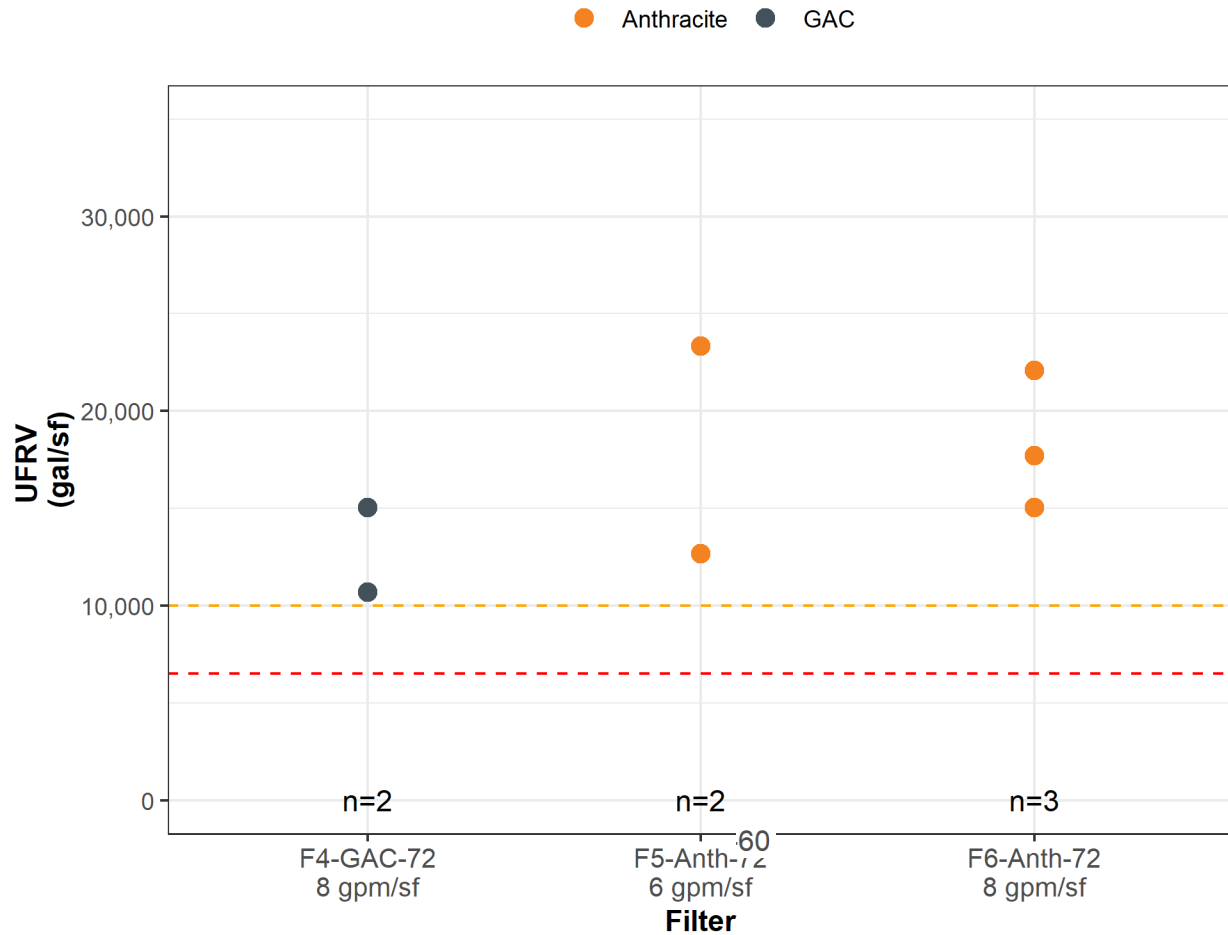


Figure 4-4. Calculated UFRVs during the initial screening of alum on Train 1 from July 1 - 8

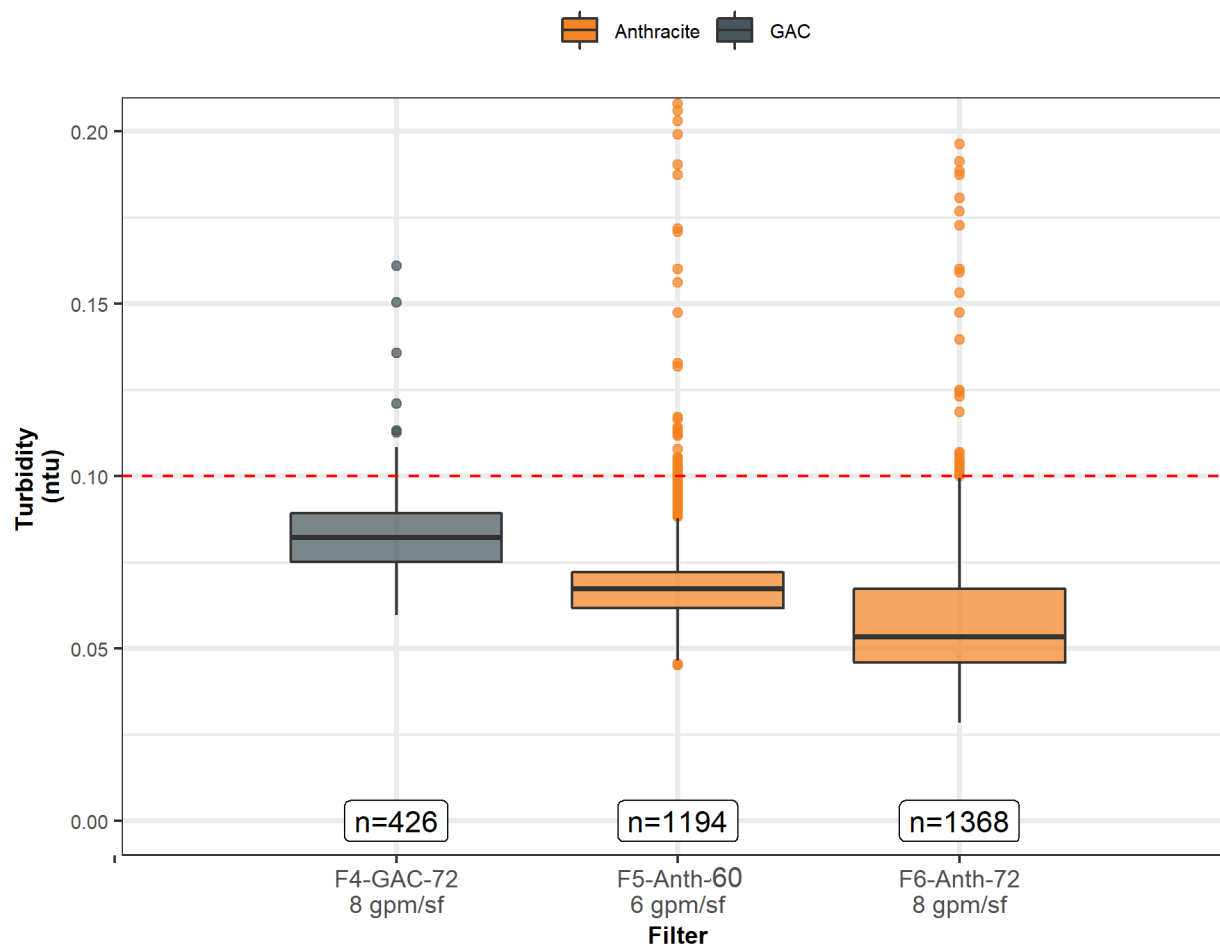


Figure 4-5. Filter effluent turbidities recorded during accepted filter runs during the initial screening of alum on Train 1 from July 1 - 8

Filter productivity was generally good during this time with coagulant only (no coagulant aid or filter aid), with UFRVs exceeding 10,000 gal/sf-run. Filter effluent turbidities were generally low on the anthracite filters (Filters 5 and 6) through the bulk of their runs. The GAC filter (Filter 4) had higher filter effluent turbidities than the anthracite filters during this test period, and correspondingly lower filter productivity. Particle count data were not available for this test condition.

Figure 4-6 summarizes average TOC, UV_{254} , and apparent color from July 1–8 when the pilot was operated at filtration rates of 6 and 8 gpm/sf. The x-axis labels for the sample locations show the media type for each filter and media depth, followed by a number representing the filtration rate in gpm/sf. Above the x-axis, the number of samples analyzed is reported (i.e., n=2). For TOC reported as less than the minimum reporting limit (MRL), the value was reported as half the MRL (0.15 mg/L). In addition, color data were also corrected for the MRL, with values less than 3 Pt-Co reported as half the MRL (1.5 Pt-Co).

During the initial testing from July 1–8, while TOC and color increased in the settled water, organics levels were reduced through filtration for all filters from the raw water. Differences in organics removal between the media types were observed during this testing period. The GAC filter removed TOC from 0.74 mg/L in the raw down to below the MRL (80 percent removal from raw water), while both anthracite filters removed TOC to approximately 0.5 mg/L (33 percent). UV_{254} was reduced more with

the GAC filter than in the two anthracite filters as well (86 percent for the GAC filter and 64 and 60 percent for the anthracite filters). On average, color was removed from the raw water following treatment. However, during this period, samples were measured for apparent color (i.e., the samples were not filtered prior to color measurement), so some settled water samples showed higher apparent color due to the influence of increased turbidity in the settled water.

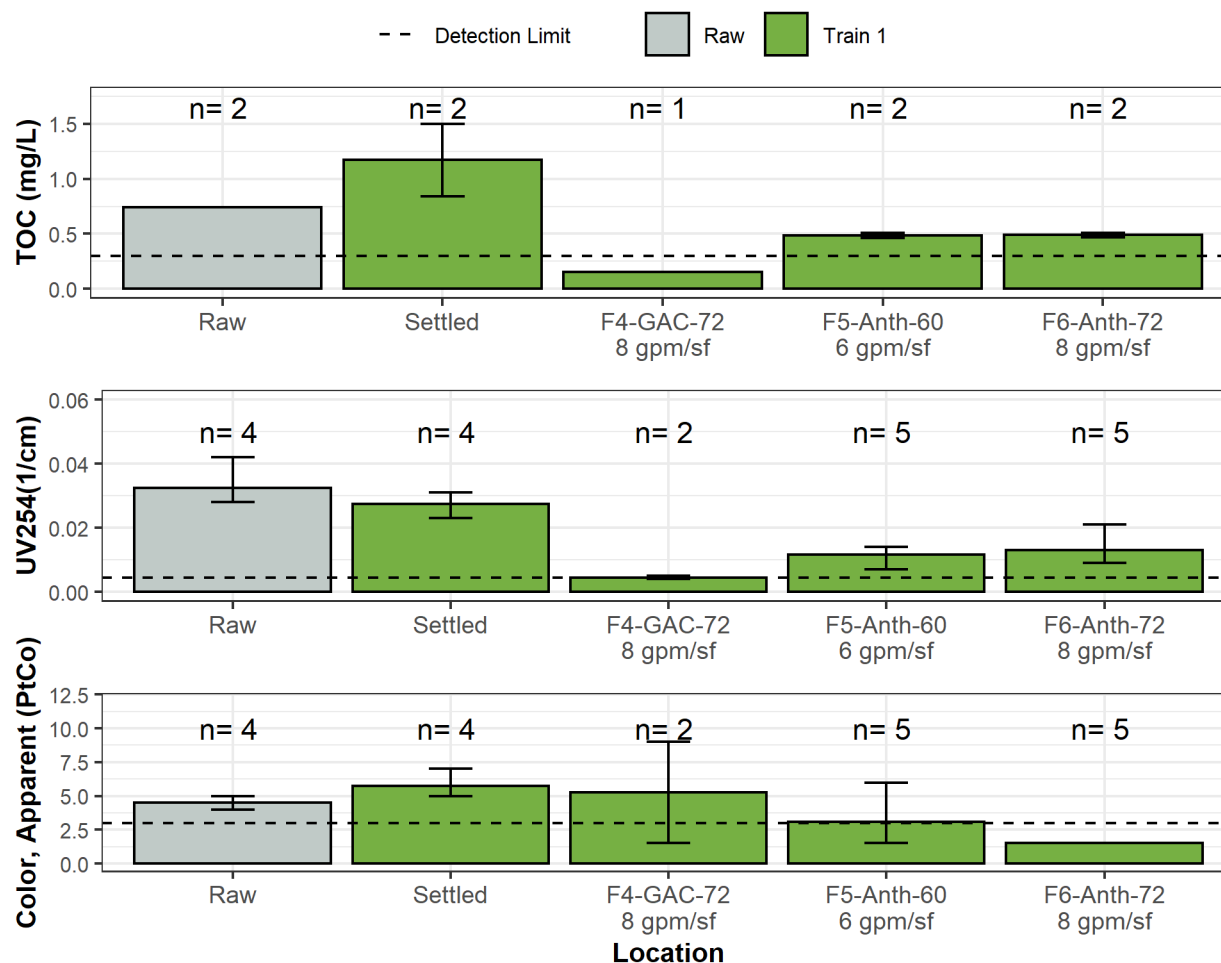


Figure 4-6. Overall organics removal performance during the initial screening of alum (July 1-8)

Average TOC, UV₂₅₄, and apparent color by location during the initial screening of alum on Train 1.

4.2.2.2 Ferric Chloride

Ferric chloride was tested during the initial testing period from June 18 to 25 while in start-stop operation. During the initial testing phase, non-ionic filter aid (Clarifloc N-6310) was necessary to get the filters to come off the FTW cycle. Based on the initial testing, a starting dose of 1.5 mg/L ferric chloride was used for the coagulant comparison trial starting on July 9, in combination with nonionic filter aid (0.01–0.05 mg/L). Cationic coagulant aid (Clarifloc C359) was added on July 12 at a dose of 1.3–1.6 mg/L for the remainder of the trial. Initially, coagulant aid showed improvement in filter operation, but this improvement was not sustained. Throughout the testing period the following ferric dosages were used: 0.8, 1.0, 1.25, 1.7, 2.3, 3.3, 4.2, and 5.8 mg/L. The ferric dosage that resulted in the highest UFRV was 1.25 mg/L, in combination with coagulant aid and filter aid.

As evidenced by the multiple ferric dose adjustments during the initial coagulant screening, it was difficult to produce acceptable water quality using ferric coagulation. Acceptable filter performance was not achieved during the ferric screening, as shown in Figure 4-7.

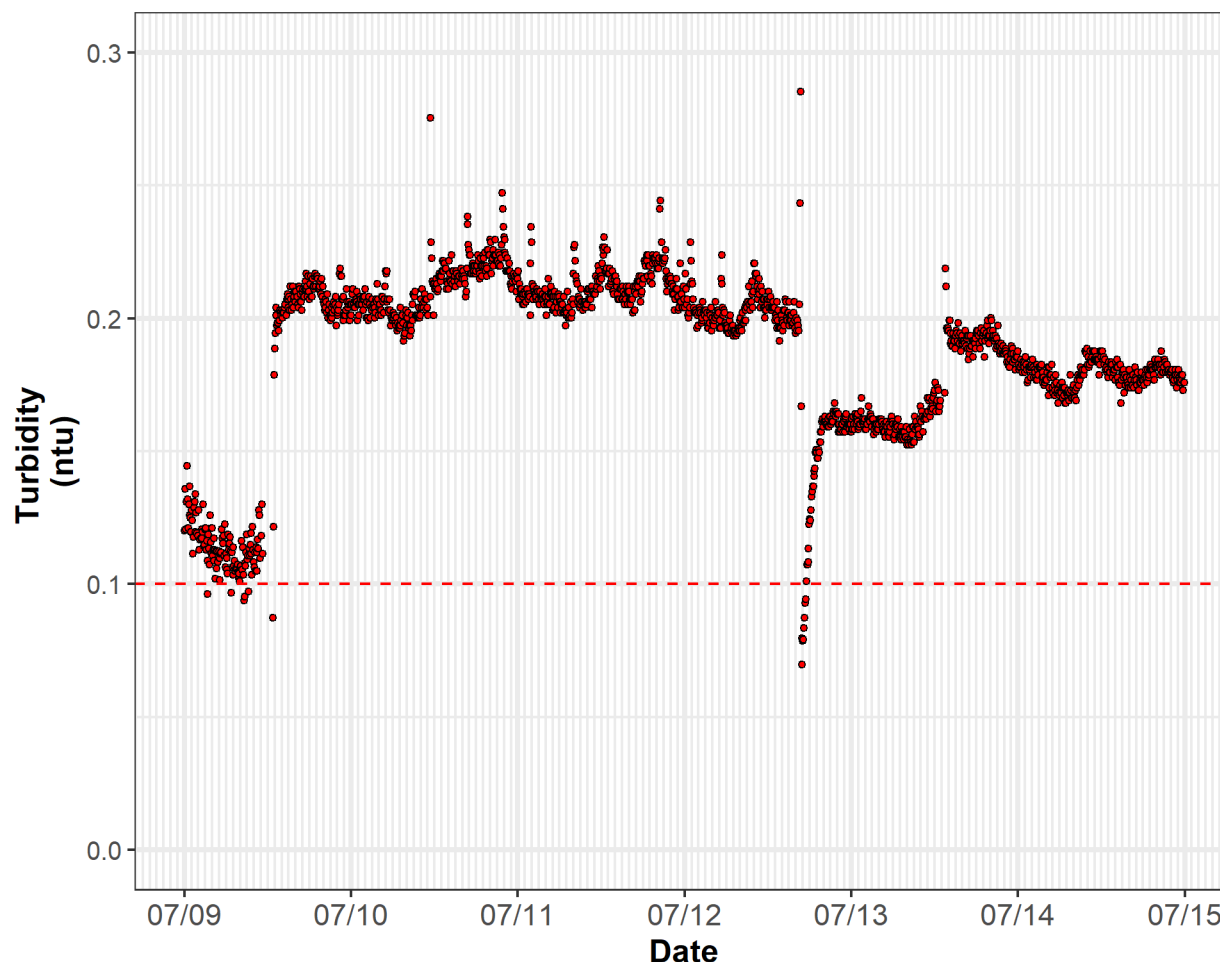


Figure 4-7. Turbidity data from Filter 3 during the initial ferric coagulant screening

These results are not intended to indicate that ferric cannot be used to effectively treat Bull Run water. Instead, they only indicate that proper conditions for use of ferric was not identified during the initial screening period. Ferric may be evaluated again during cold water testing, and now that the pilot has an SCM available, it may be possible to improve the ferric dose to achieve acceptable filter performance.

Organics removal across the treatment process is summarized in this section, when ferric chloride was dosed as the coagulant. Figure 4-8 summarizes average TOC, UV_{254} , and apparent color from July 9–15 when the pilot was operated at the low filtration rate regime (6 and 8 gpm/sf).

Removal of organics with ferric was limited compared to performance with the other coagulants tested. Effectively, treatment did not remove TOC from the raw water beyond what was removed in the GAC columns (presumably because the adsorptive capacity of the GAC had not yet been exhausted). This supports the generally finding that ferric coagulant was ineffective, either because the coagulant dose was off or the coagulation pH was above the 5.5 to 6.5 range that is optimum for ferric coagulants. Accordingly, color and UV_{254} were not removed in the filters. At times, ferric added yellow color that

could be visually seen in operation and was also measured, even at low ferric dosages. This is also indicative that the coagulant remained as dissolved iron instead of precipitating as iron hydroxide.

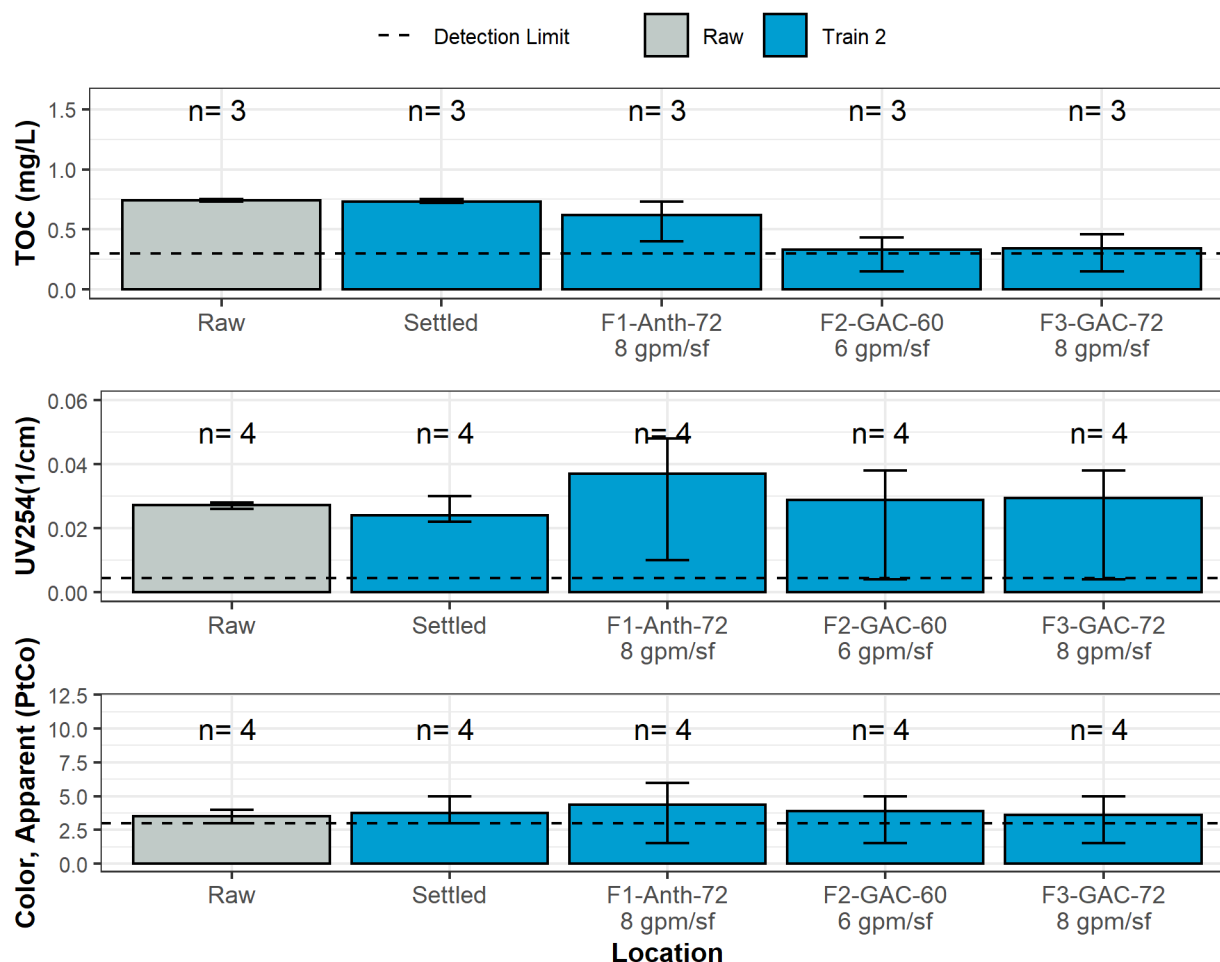


Figure 4-8. Overall organics removal performance during the initial ferric coagulant screening, July 9 - 15

Average TOC, UV₂₅₄, and apparent color by location during the initial ferric coagulant screening in Train 2.

4.2.2.3 PACI – Initial Screening

PACI was initially tested during start-stop operation at a dose of 3.0 mg/L based on bench-scale jar testing performed prior to the pilot testing. PACI was tested again from July 9–15 with continuous operation at filtration rates of 6 and 8 gpm/sf. During this initial testing period, PACI was dosed between 2.5 and 3 mg/L with non-ionic filter aid (Clarifloc N-6310) dosed between 0.01–0.03 mg/L.

Similar to the initial alum screening, pilot operations during the initial PACI screening limited the number of filter runs collected. This was compounded by mechanical issues with Filter 4 that limited operations during this period. UFRVs calculated for the filter runs collected during the initial PACI screening are shown in Figure 4-9. UFRVs were high during this testing period with UFRVs exceeding 10,000 gal/sf-run. During this limited testing, the 8 gpm/sf anthracite filter had the best performance.

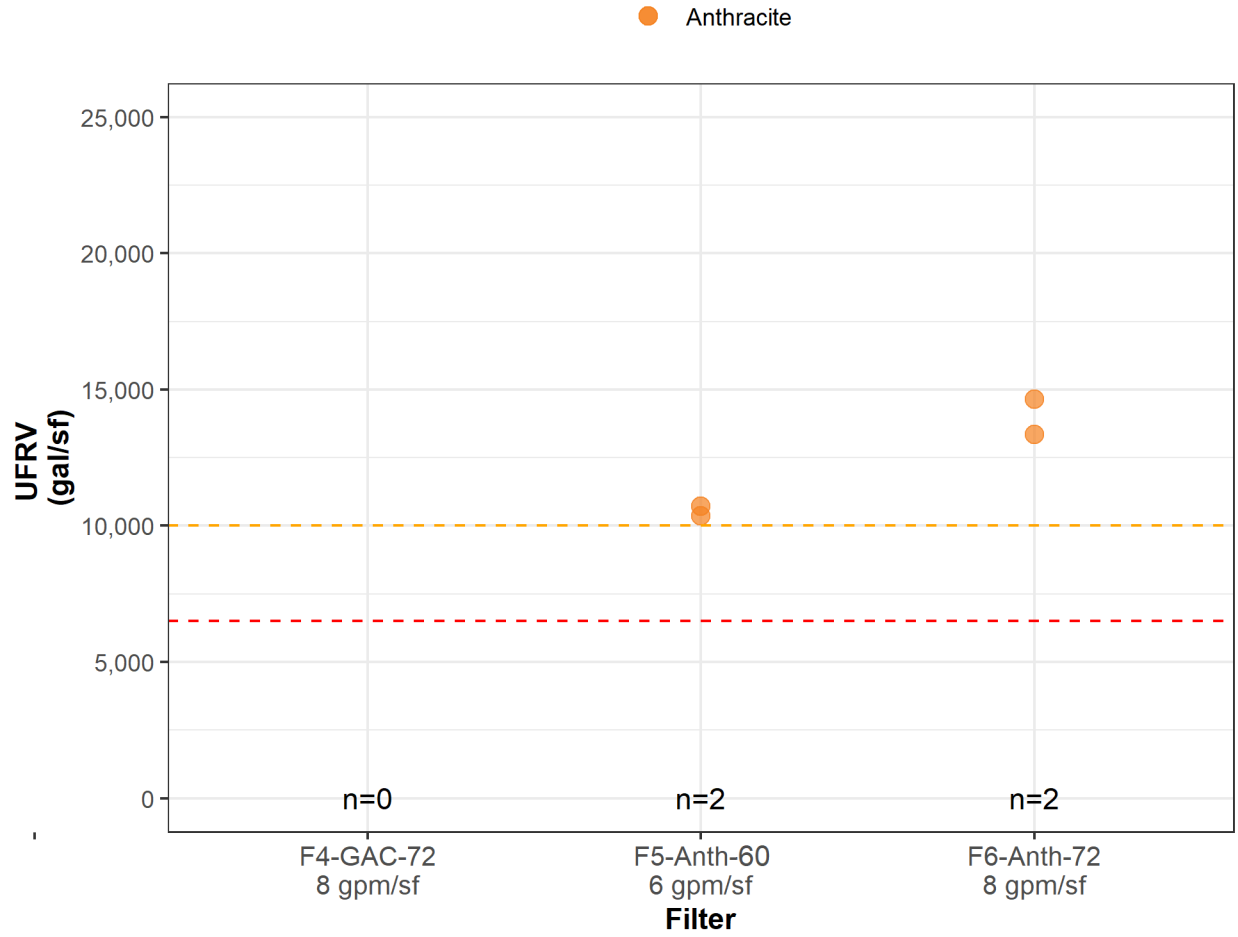


Figure 4-9. Calculated UFRVs during the initial screening of PACI on Train 1 from July 9 - July 15

Filter effluent turbidities recorded during the filter runs shown in Figure 4-9 are summarized in Figure 4-10. Both anthracite filters maintained a median filter effluent turbidity near 0.05 NTU during these runs.

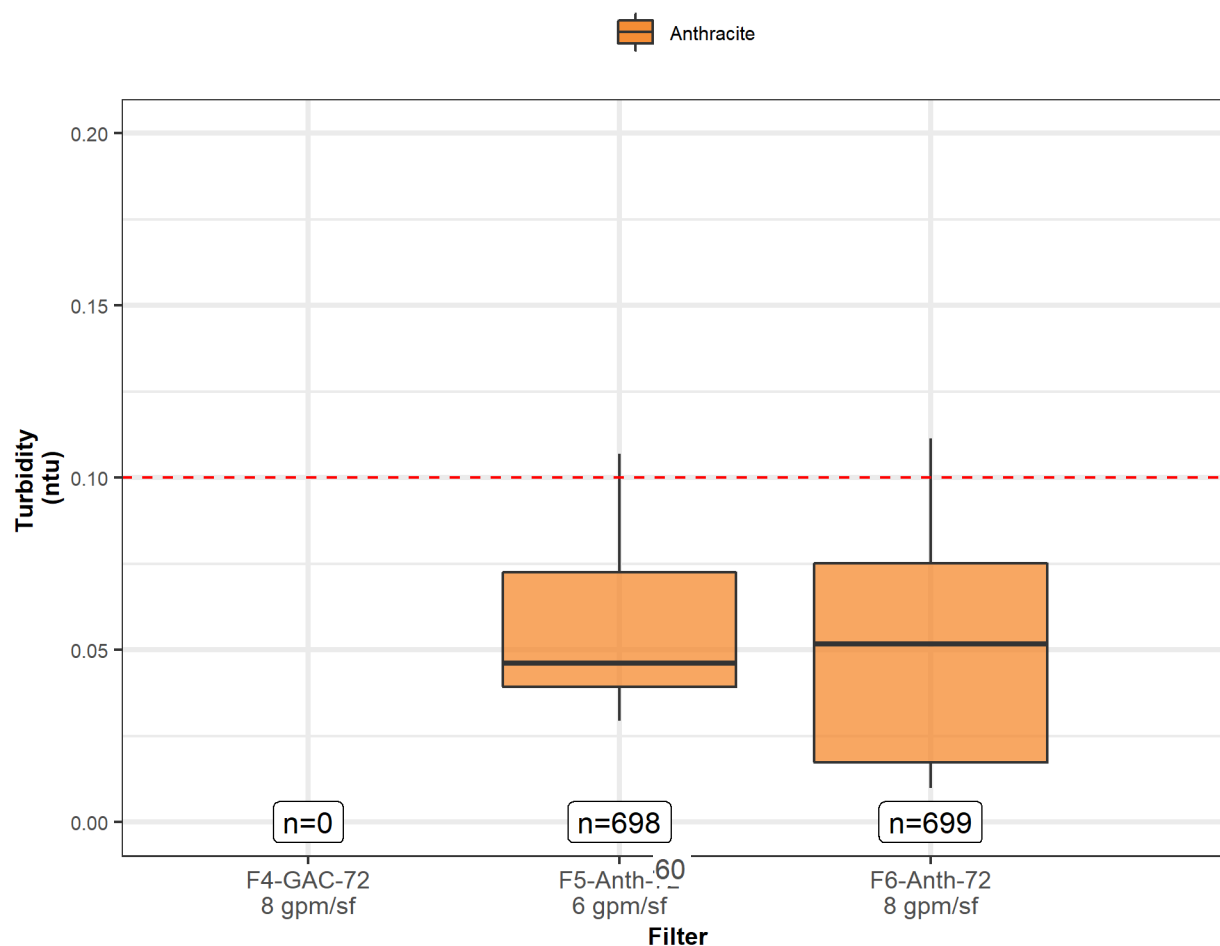


Figure 4-10. Filter effluent turbidities recorded during accepted filter runs during the initial screening of PACI on Train 1 from July 9 - July 15

Average TOC, UV_{254} , and apparent color from July 9–15, prior to the filtration rate change, are summarized in Figure 4-11. As mentioned above, Filter 4 (GAC at 8 gpm/sf) had mechanical issues that limited operations during this period, therefore no data are presented for that filter. For the initial testing period, the anthracite filters (Filters 5 and 6) removed TOC to 0.41 mg/L and 0.46 mg/L respectively (41 percent removal on average). UV_{254} was also reduced through filtration by an average of 62 percent for both anthracite filters. Color was also substantially removed in the anthracite filters.

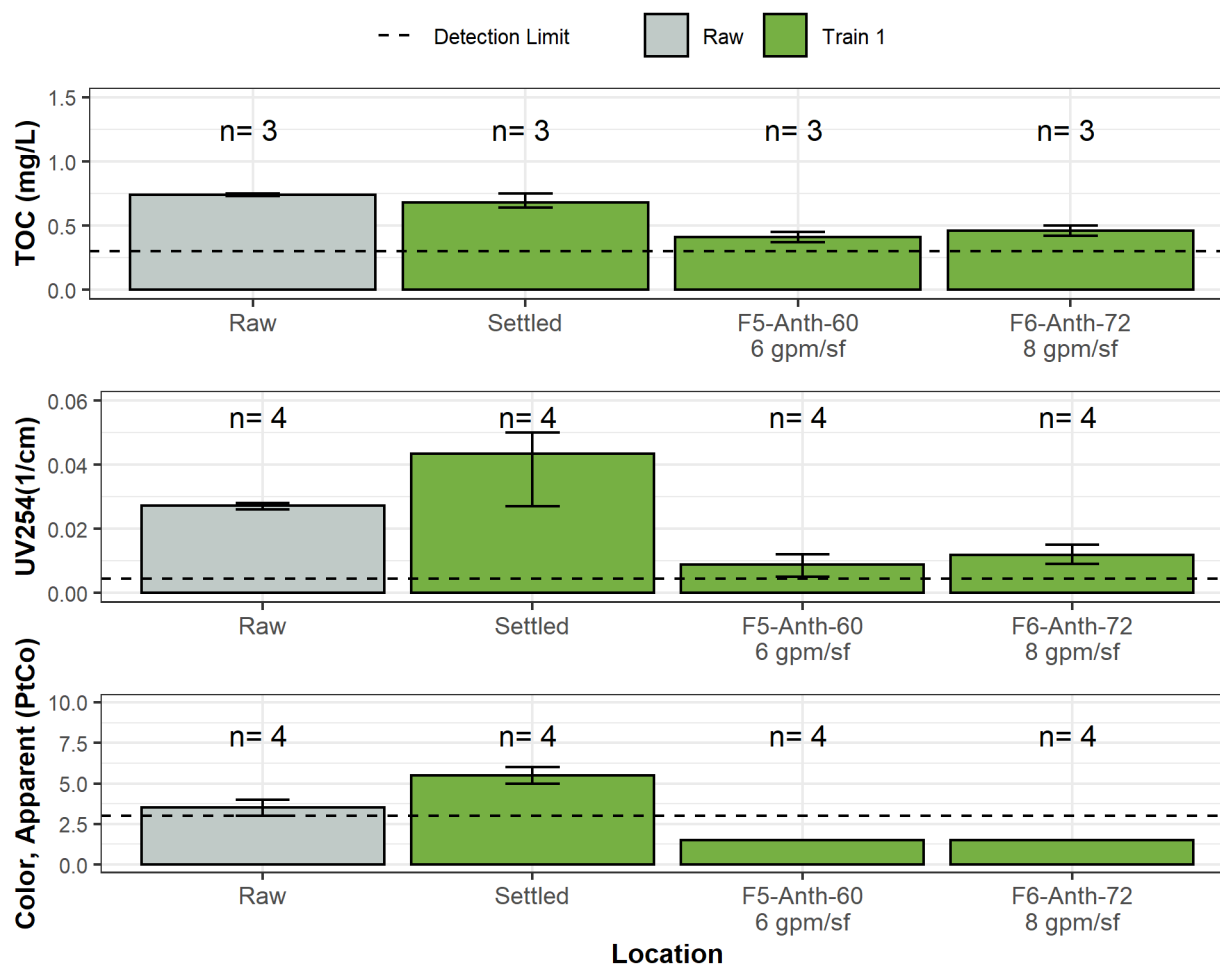


Figure 4-11. Overall organics removal performance with PACI during the initial screening of PACI, July 9 - 15
 Average TOC, UV₂₅₄, and apparent color by location when PACI during the initial screening of PACI in Train 1. Filter 4 (F4-GAC-72) had mechanical issues during this time period and was not operational.

4.2.2.4 ACH 7

ACH was initially tested during start-stop operation at doses of 1.7 and 2.5 mg/L. A 1.7 mg/L ACH dose resulted in longer filter runs than 2.5 mg/L and was selected for the comparison trial from July 1–8. Filter aid was added on July 6, at a dose of 0.02 mg/L for the remainder of the testing period.

As with the alum and PACI screening, operations during the initial screening of ACH limited the number of filter runs observed during the test period. However, compared to the alum and PACI tests, the ACH tests were characterized by relatively short filter runs followed by extended breakthrough of turbidity, as illustrated in Figure 4-12. These short runs resulted in more runs occurring during the test period, as reflected in Figure 4-13.

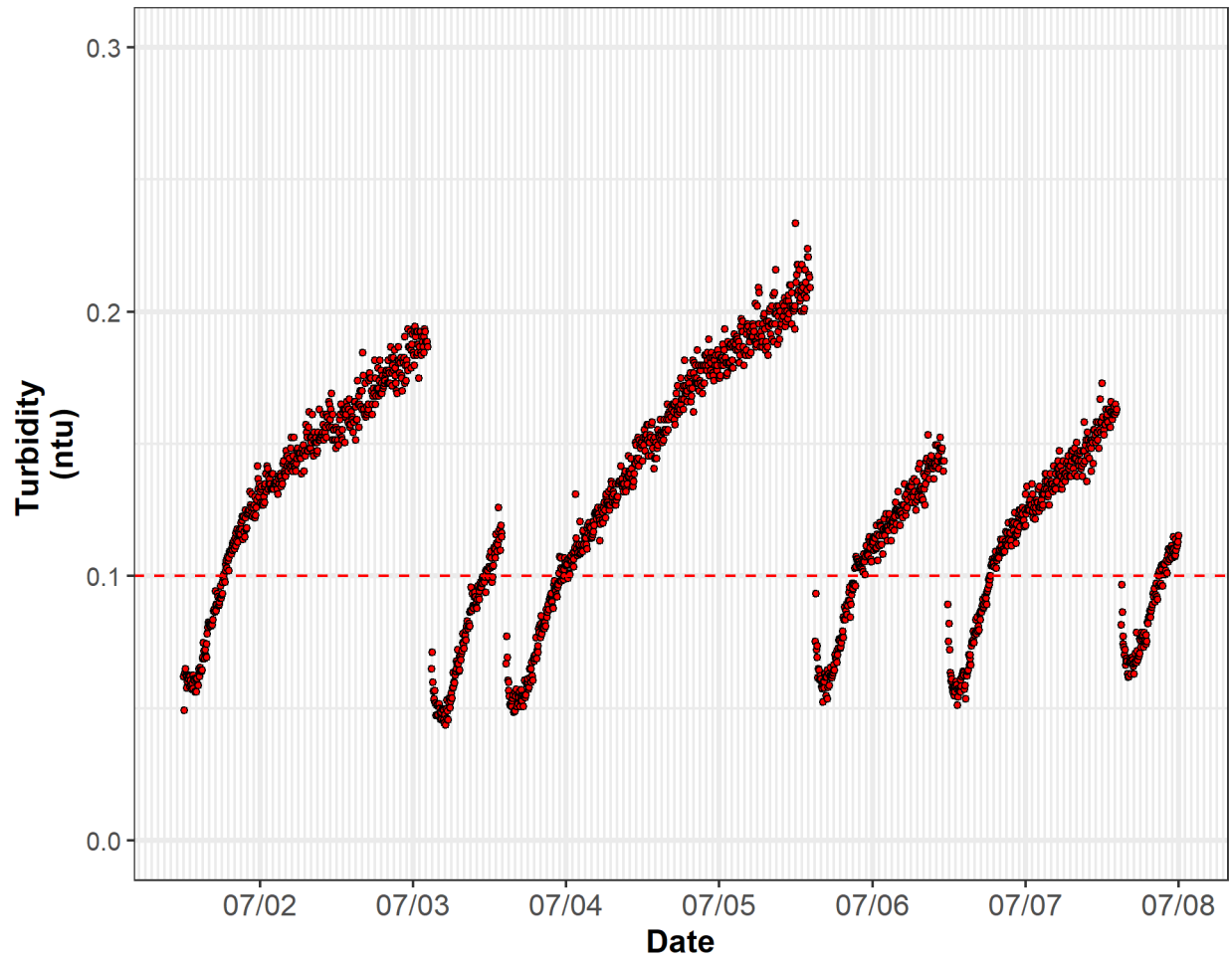


Figure 4-12. Turbidity data from Filter 3 during the initial ACH coagulant screening

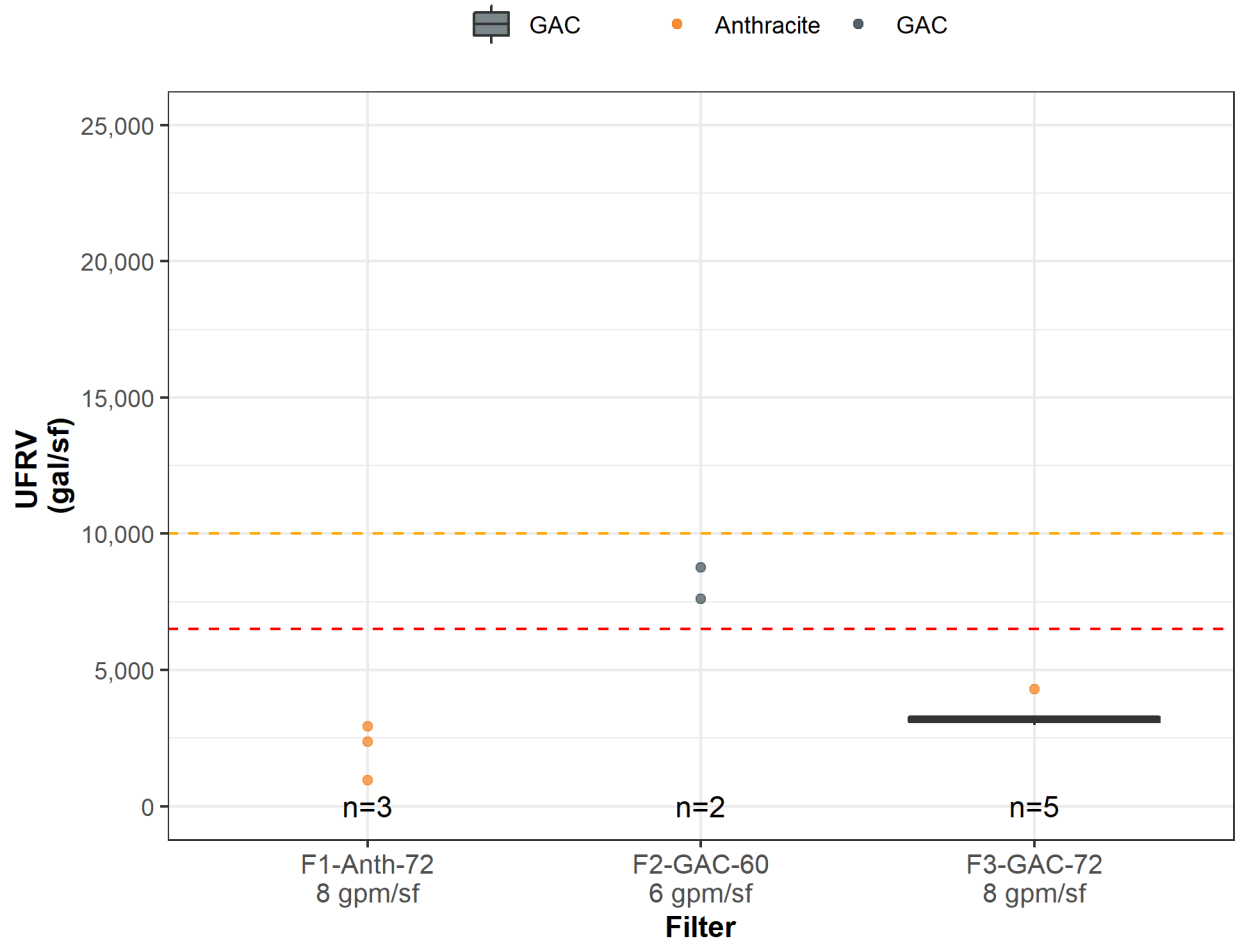


Figure 4-13. Calculated UFRVs during the initial screening of ACH on Train 2 from July 1 – 8

Filter effluent turbidities corresponding to the filter runs shown in Figure 4-13 are summarized in Figure 4-14. Overall, filter effluent turbidities were relatively high, with median filter effluent turbidities in all three filters ranging between 0.07 to 0.08 NTU.

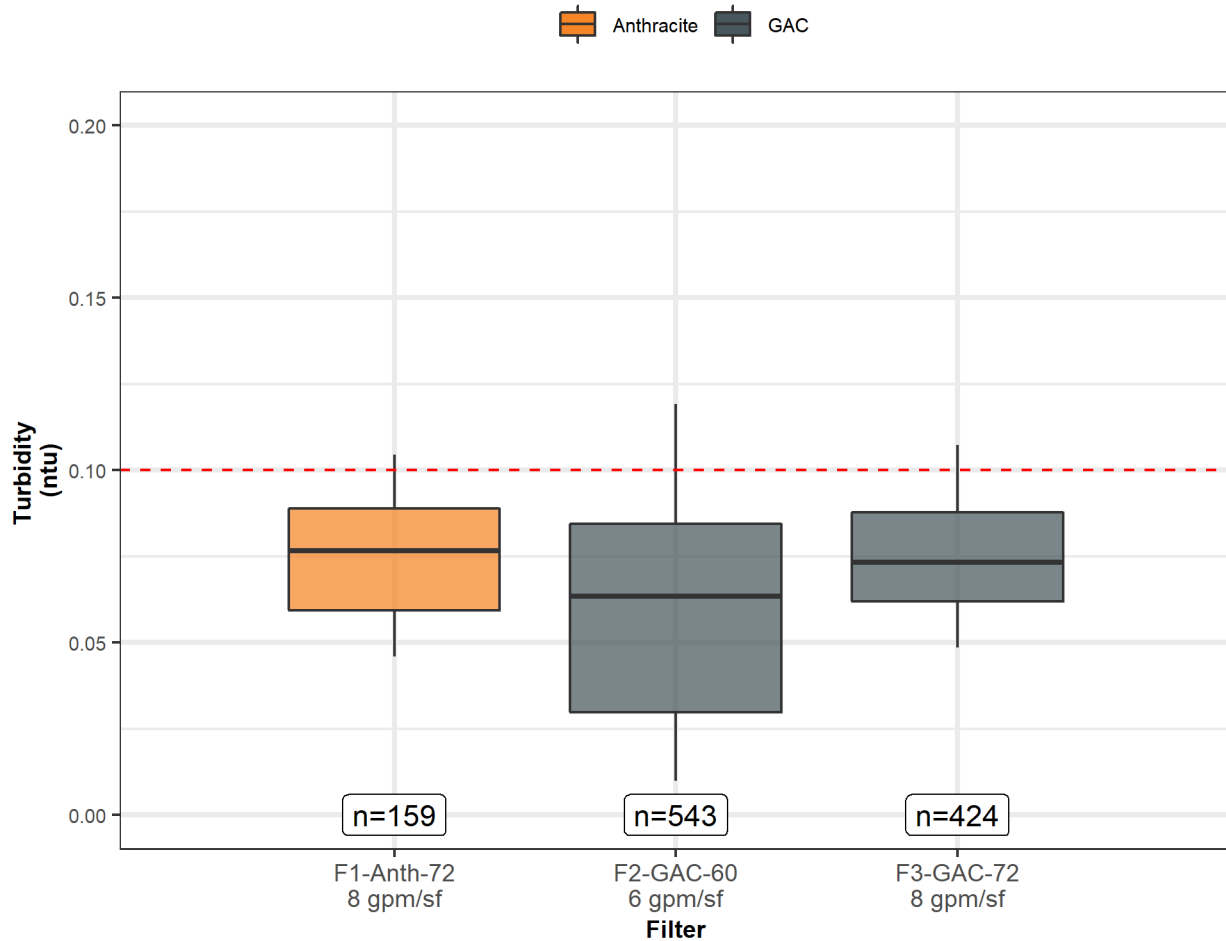


Figure 4-14. Filter effluent turbidities recorded during accepted filter runs during the initial screening of ACH on Train 2 from July 1 – 8

Organics removal across the treatment process are summarized in this section, when ACH was tested. Figure 4-15 summarizes average TOC, UV_{254} , and apparent color from July 1–8 when the pilot was operated at filtration rates of 6 and 8 gpm/sf. The GAC filters reduced TOC from raw water by 70 and 80 percent, respectively, compared to the anthracite filter, which removed TOC by about 34 percent. All the filters had excellent UV_{254} removal with removals of 63 percent and 64 percent for the anthracite filter and the GAC Filter 2, and 84 percent removal for the GAC Filter 3. Color removal was more limited compared to TOC and UV_{254} for all the filters. The GAC filters removed color by 33 and 8 percent for Filters 2 and 3 respectively, while the anthracite filter removed color by 22 percent. Settled water TOC and color increased from the raw water, prior to removal through filtration. As with the initial Alum screening, samples were measured for apparent color (i.e. the samples were not filtered prior to color measurement), so some settled water samples showed higher apparent color due to the influence of increased turbidity in the settled water.

ACH was not selected for further testing during the fall season as a result of short filter run times because of turbidity breakthrough, and slightly lower color removal compared to the filter performance with alum and PACl.

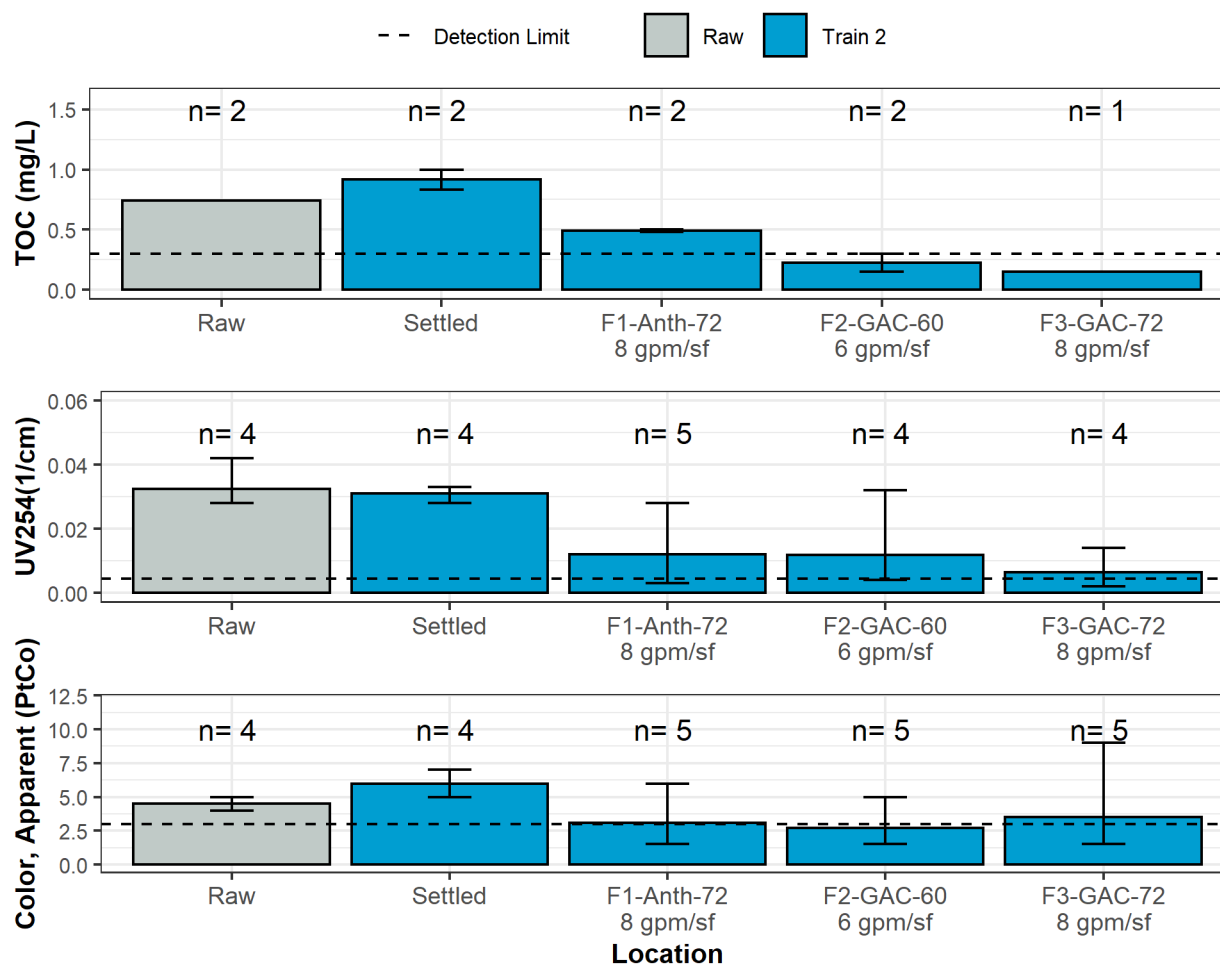


Figure 4-15. Overall organics removal performance during the initial screening of ACH, July 1-8

Average TOC, UV₂₅₄, and apparent color by location when ACH was dosed as the primary coagulant in Train 2.

4.2.2.5 Alum vs. PACl Side-by-side Comparison

Following the initial period of coagulant comparison, it was apparent that, under the conditions tested, alum and PACl offered better performance than had been obtained when using ferric chloride or ACH as the primary coagulant. Further evaluation of these two coagulants was conducted with each treating the same water under similar conditions, with PACl in Train 1 (Filters 4, 5, and 6) and alum in Train 2 (Filters 1, 2, and 3). The conditions tested during this side-by-side evaluation are summarized in Table 4-2. Testing started with coagulant and filter aid, followed by a period of testing without filter aid, and the addition of coagulant aid. Based on an observed degradation in performance without filter aid, the treatment chemicals were adjusted to include filter aid. The coagulant comparison testing concluded with the addition of pre-ozonation to both trains.

The following sections present the results from the side-by-side comparison in terms of UFRVs and filter effluent turbidities through July 31, and UFRVs, filter effluent turbidities and filter effluent particle counts for the remaining testing scenarios. Organics removal during the side-by-side comparison are summarized for the full comparison testing period at the end of this section.

Table 4-2. Summary of chemical dosing scenarios for alum and PACI comparison

Test Duration ^a	Alum (Train 2)			PACI (Train 1)		
	Coagulant Dose as Alum (mg/L)	Coagulant Aid ^b Dose (mg/L)	Filter Aid ^c Dose (mg/L)	Coagulant Dose as PACI (mg/L)	Coagulant Aid ^b Dose (mg/L)	Filter Aid ^c Dose (mg/L)
July 15 – 26 (filtration rates at 6 and 8 gpm/sf)	4.15 – 5	---	0.01 - 0.03	1.6-3	---	0.01 – 0.03
July 26 – 29 (Start of higher filter rate operation: 8 and 12 gpm/sf)	5.1	---	0.02	1.75	---	0.015
July 30 – August 1	5.1	0.4 – 0.6	---	1.75	0.25 – 1.0	---
August 1 – 5	1.65 – 3	0.5 – 2.2	---	1.75	0.25	---
August 5 – 8	1.5	0.4	0.015	1.0	0.25	0.015
August 8 – 12	5.1 – 7.0	---	0.015	2.3	---	0.015
August 20 – 30 (pre-ozonation at 0.5 mg/L)	2.0	0.4	0.015	2.3	---	0.015-0.2

a. A shutdown period occurred from August 12–20 due to mechanical issues with the ozone module.

b. Cationic polymer Clarifloc C359 was tested as the coagulant aid.

c. Nonionic polymer Clarifloc N-6310 was tested as the filter aid.

Filtration Rates of 6 and 8 gpm/sf

The initial round of side-by-side testing was conducted at filtration rates of 6 and 8 gpm/sf, the same filtration rates used for the prior coagulant screening periods. This testing was conducted from July 15–26, and the calculated UFRVs from this period are presented in Figure 4-16.

The initial side-by-side comparison of alum and PACI presents mixed results. For both the deeper GAC and anthracite filters operating at 8 gpm/sf, the PACI UFRVs are slightly higher than the Alum UFRVs. However, the shorter GAC filter operating at 6 gpm/sf with alum addition outperformed the shorter anthracite filter at 6 gpm/sf with PACI addition by a substantial margin. All filters indicated performance above the 6,500 gal/sf-run UFRV requirement, while many runs exceeded 10,000 gal/sf-run.

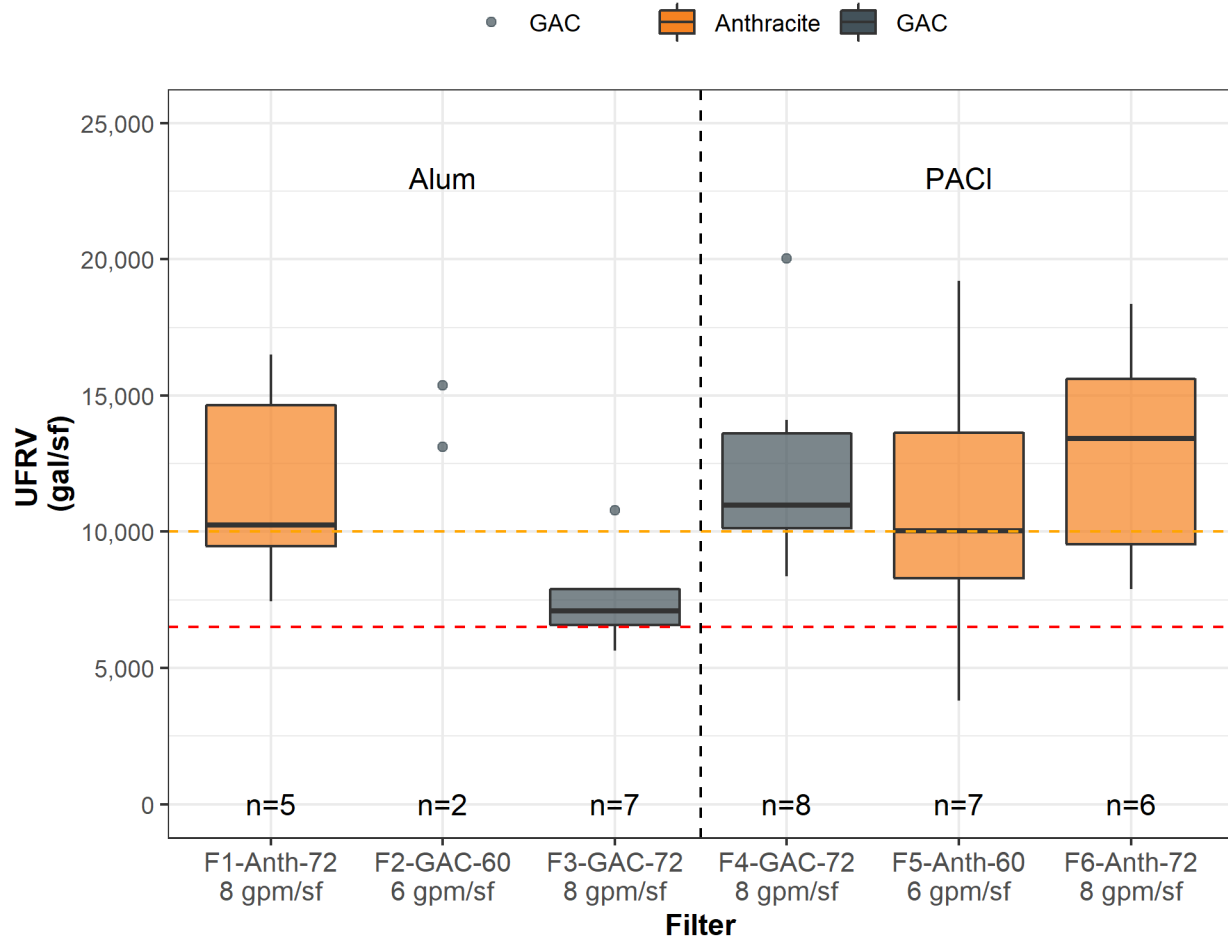


Figure 4-16. Calculated UFRVs during the side-by-side testing of alum and PACI at 6 and 8 gpm/sf, conducted from July 15 –26

Filter effluent turbidities from both trains during accepted filter runs are summarized in Figure 4-17. Interestingly, the filter effluent boxplot shown for Filter 1 appears to be incongruous with the criteria used to truncate filter runs for UFRV calculations, as discussed in Section 4.1.1; the algorithm should limit the data above 0.10 NTU to no more than 5 percent of the total filter run, but Figure 4-17 indicates that the upper quartile of filter effluent turbidity data from Filter 1 is above the 0.10 NTU threshold. The cause of this discrepancy can be seen in Figure 4-18. Because Filter 1 had extended ripening curves during which filter effluent turbidities were consistently near the 0.10 NTU threshold for the runs recorded during this period, the algorithm did not correctly truncate the run when more than 5 percent of the total filter effluent turbidity data recorded exceeded 0.10 NTU during the run. By a strict interpretation of the criteria used to calculate UFRVs, none of the runs from Filter 1 during this period should have been accepted.

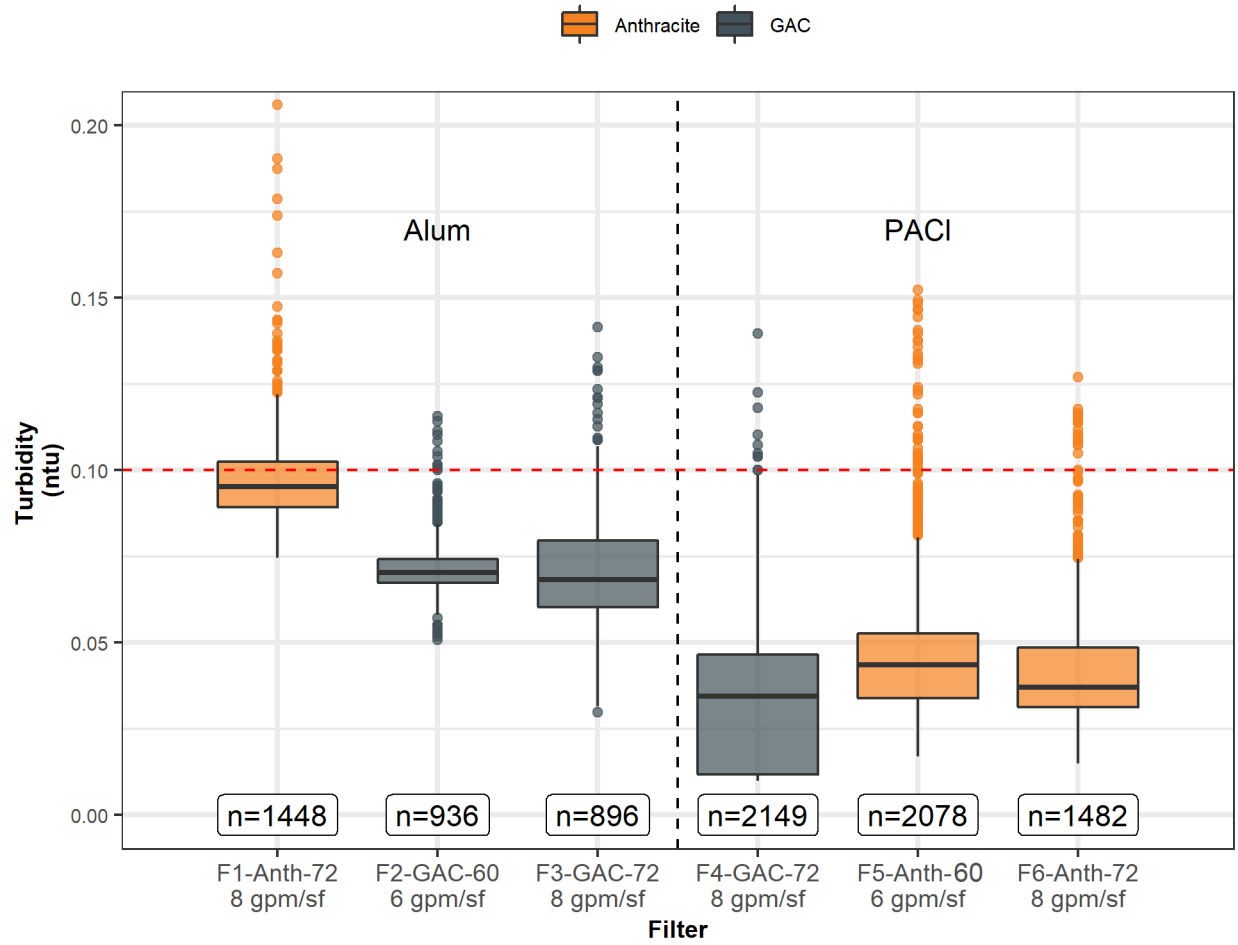


Figure 4-17. Filter effluent turbidities recorded during accepted filter runs during the side-by-side testing of alum and PACI at 6 and 8 gpm/sf, conducted from July 15 –26

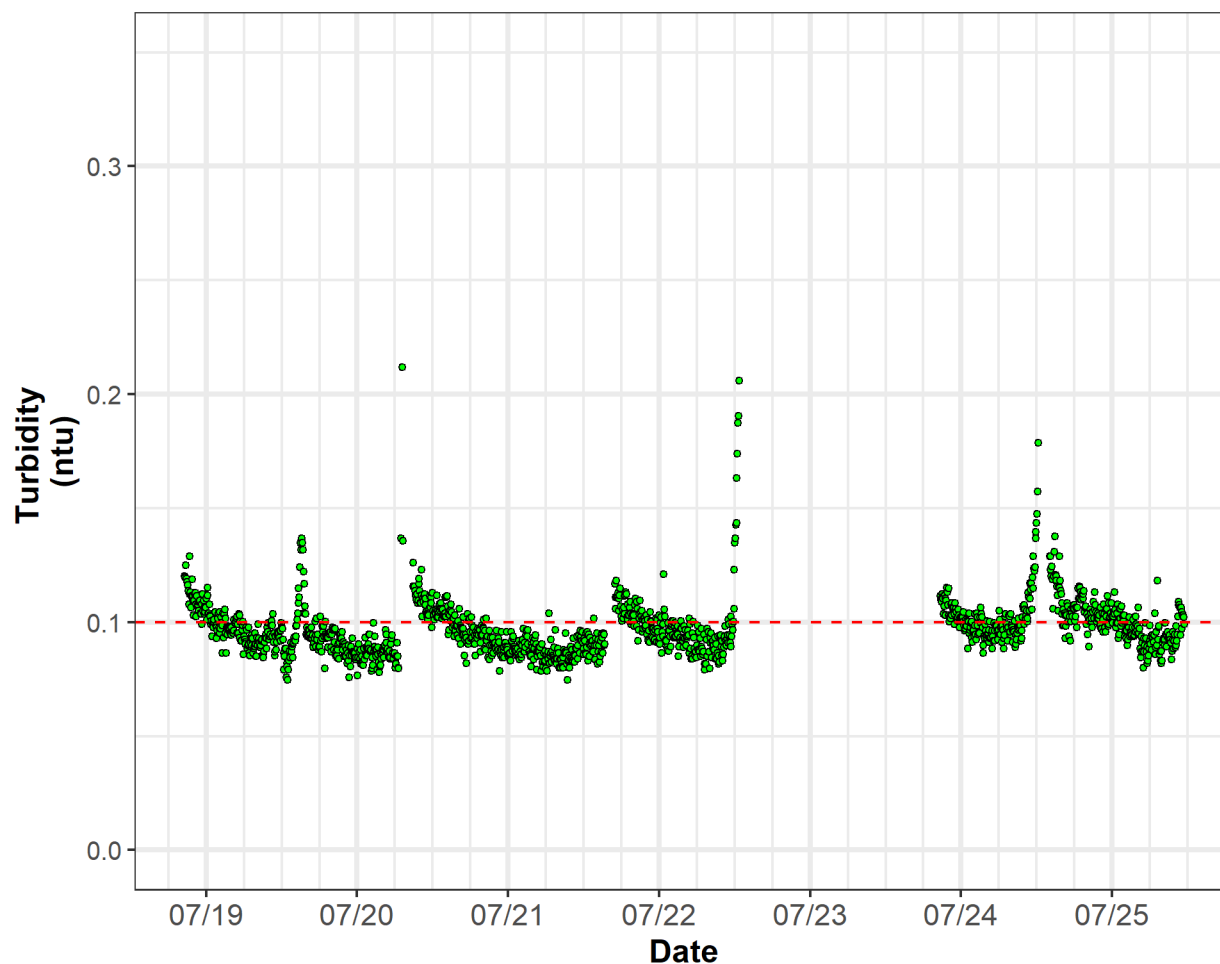


Figure 4-18. Filter effluent turbidity over time from Filter 1 during accepted filter runs during the side-by-side testing of alum and PACl at 6 and 8 gpm/sf, conducted from July 15 –26

Filtration Rates of 8 and 12 gpm/sf

On July 26, the filtration rates on all filters were increased. The 72-inch filters (Filters 1, 3, 4, and 6) were increased from 8 to 12 gpm/sf, while the 60-inch filters (Filters 2 and 5) were increased from 6 to 8 gpm/sf. Calculated UFRVs from this period are presented in Figure 4-19.

The initial runs conducted at filtration rates of 8 and 12 gpm/sf have remarkably consistent UFRVs. All three filters receiving water treated with PACl had higher productivity (e.g., higher UFRVs) than those receiving water treated by alum. As with the preceding condition, the deep GAC filter on the train with alum pre-treatment, now operating at 12 gpm/sf, had the lowest UFRV. The other two filters on the alum train (Filters 1 and 2) did not produce any acceptable runs during this period due to excessive turbidity; the filter effluent turbidity from Filter 1 was consistently near or above 0.10 NTU, while the turbidity from Filter 2 was consistently higher than that.

In general, operating at higher filtration rates did not appear to impact performance of any of the filters receiving water that had been treated with PACl. All filters on that train exceeded 10,000 gal/sf-run and produced acceptable filtered effluent turbidity. Of the three filters receiving water treated with alum, only the deep GAC filter (Filter 3) produced filter runs that met the acceptance criteria. These runs were generally shorter than those on the other train.

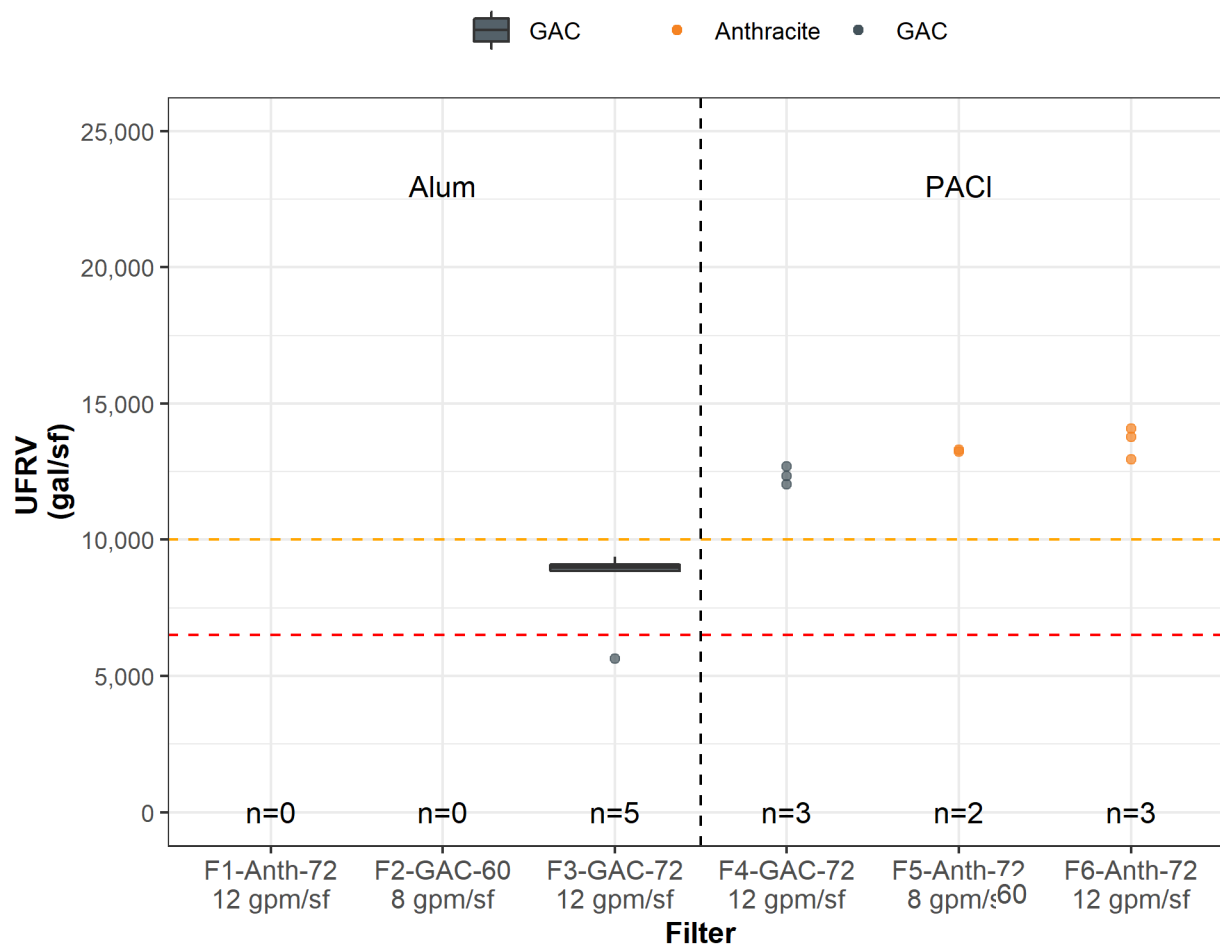


Figure 4-19. Calculated UFRVs during the side-by-side testing of alum and PACI at filtration rates of 8 and 12 gpm/sf, conducted from July 26 –30

Filter effluent turbidities recorded during this test period are summarized in Figure 4-20. Effluent turbidities from Filters 1 and 2 are not shown because they exceeded the 0.10 NTU threshold throughout the duration of the filter runs during this period, so none of those runs met the acceptance criteria.

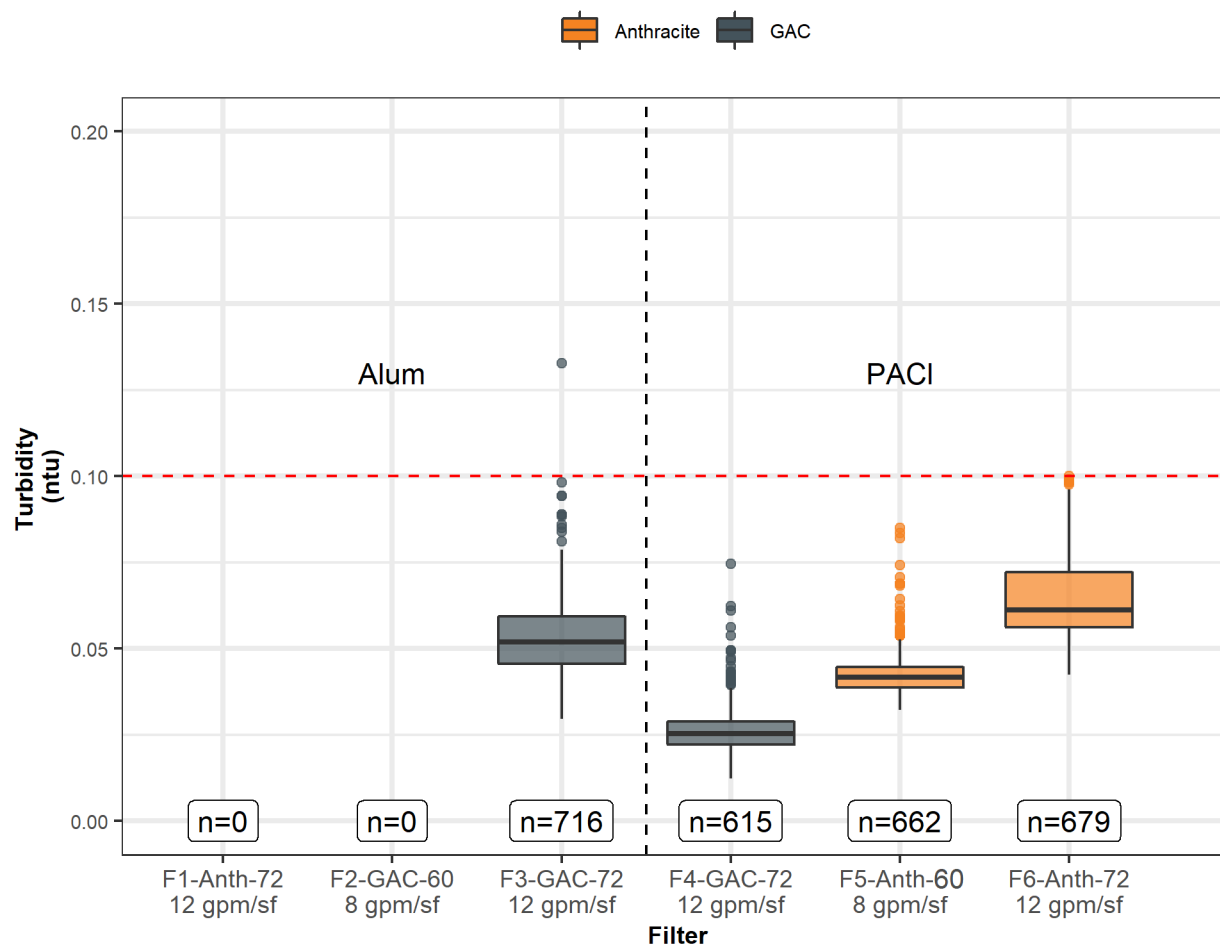


Figure 4-20. Filter effluent turbidities recorded during accepted filter runs during the side-by-side testing of alum and PACl at filtration rates of 8 and 12 gpm/sf, conducted from July 26 –30

Without Filter Aid

After moving to the higher filtration rates, a brief test period was conducted to determine how the filters would perform without a filter aid polymer. During this time, cationic coagulant aid was dosed between 0.25 to 1.0 mg/L. This testing was conducted from July 30–August 5. During this period, a number of runs were terminated early due to operational modifications. Additionally, a number of runs during this period were censored from the dataset because of excessive turbidities. This is attributable either to instrument drift (due to fouling, condensation, etc.) or because the treated water could not be effectively filtered without filter aid polymer. For these reasons, during this period none of the 12 attempted Filter 1 (anthracite, 12 gpm/sf) runs nor any of the six attempted Filter 2 (GAC, 8 gpm/sf) runs met the criteria for data acceptance.

In general, without the addition of filter aid, performance suffered. As can be seen in Figure 4-21, filter performance became much less consistent, with wider spread in UFRVs between filter runs. Filters 1 and 2 are not included on the figure because there were no acceptable filter runs during this time period due to filter effluent turbidities consistently at or above 0.10 NTU.

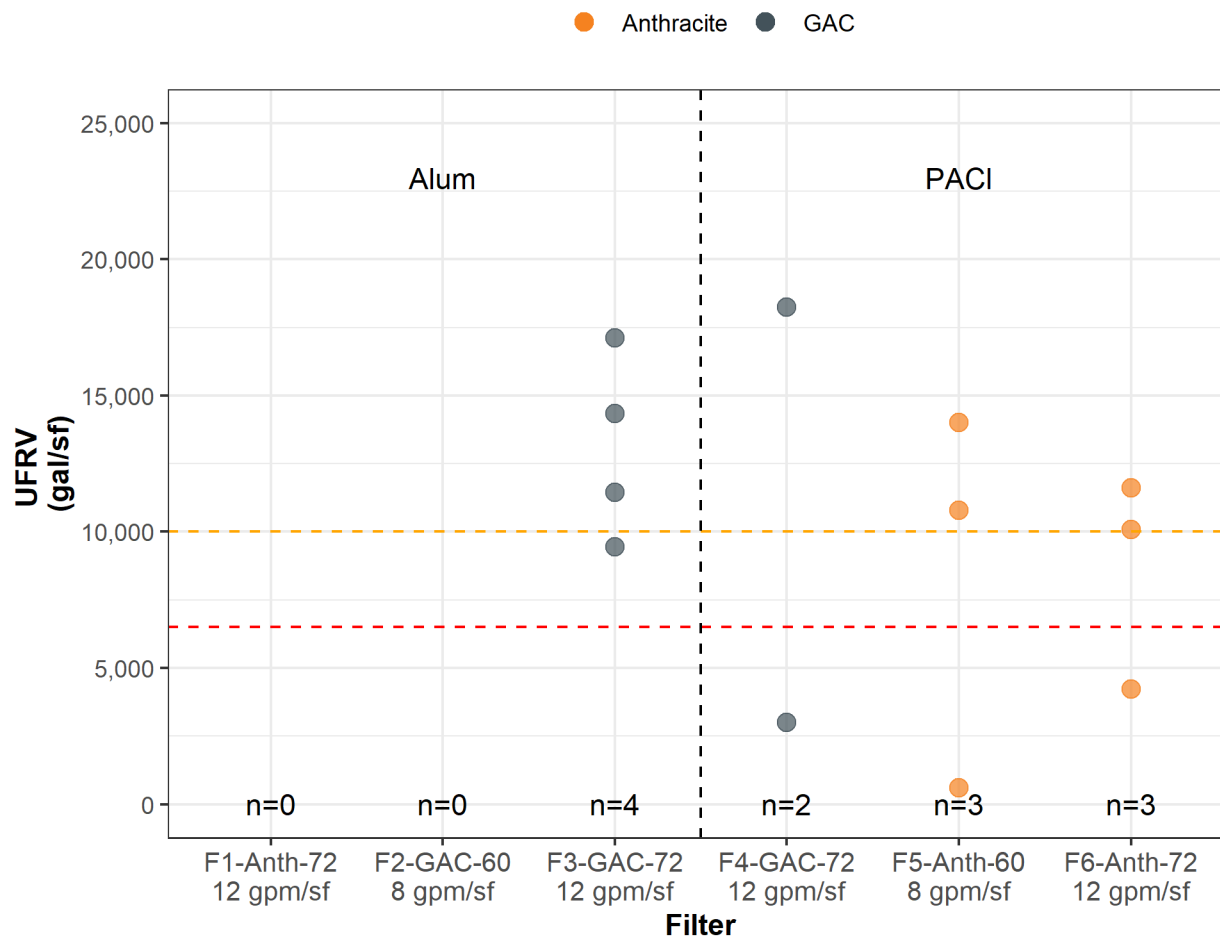


Figure 4-21. Calculated UFRVs during side-by-side testing of alum and PACI with no filter aid, from July 30 – August 5

Filters 1 and 2 are excluded from the figure due to no acceptable filter runs during this time period

Figure 4-22 summarizes the filter effluent turbidities recorded during the period comparing alum and PACI coagulation with coagulant aid, but no filter aid. As discussed previously, due to high filter effluent turbidities neither Filter 1 nor Filter 2 had any accepted runs during this time period. While Filter 3 did produce four acceptable runs, the peak filter effluent turbidities recorded at the end of the runs (during turbidity breakthrough) were considerably higher than those observed during previous test periods. The Train 1 filters (Filters 4 – 6), on the other hand, did not experience high turbidity peaks at the end of the filter runs. These data suggest that, in the absence of filter aid polymer, PACI is a more effective coagulant at controlling filter effluent turbidity than alum.

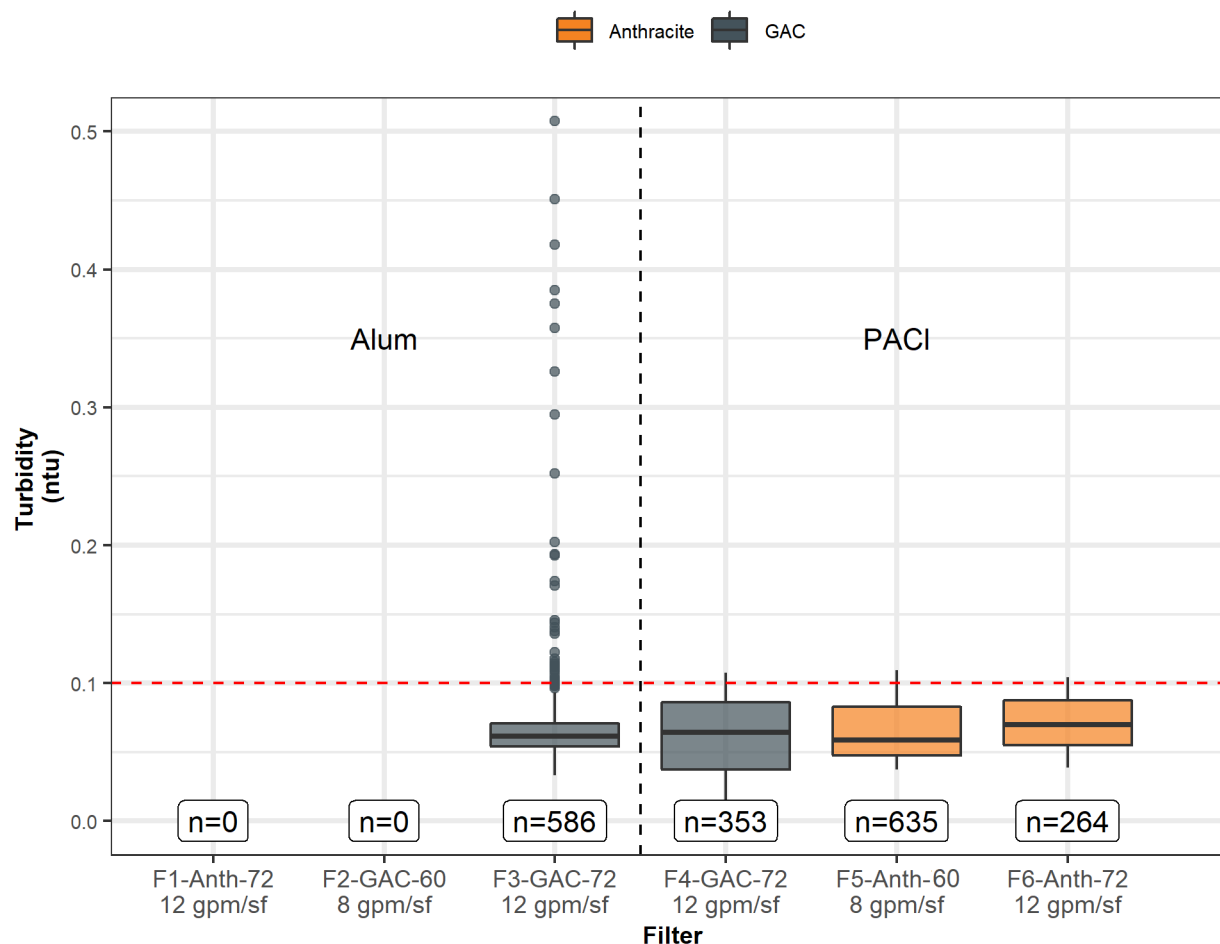


Figure 4-22. Filter effluent turbidities recorded during accepted filter runs during the side-by-side testing of alum and PACl with no filter aid, from July 30 – August 5

The particle counters on both Floc/Sed Module 1000 and the Filtration Module were calibrated on July 31. Thus, this is the first test period during which reliable particle count data were available. During this test period, there were no accepted runs on Filter 2, and the accepted run on Filter 1 occurred prior to July 31. For the remaining filters, a summary of filter effluent particle count data is presented in Table 4-3.

As a Bin 1 system, PWB would be required to achieve 2-log removal of *Cryptosporidium* and 2.5-log removal of *Giardia*. For pilot testing, particles in the 3 to 5 μm bin are considered a surrogate for *Cryptosporidium*, while those in the 5 to 15 μm bin are a surrogate for *Giardia*. However, because the Bull Run source is naturally low in particles, it is extremely difficult to demonstrate removal of particles at that level strictly because there are insufficient particles in the raw water. Therefore, the Work Plan established an alternate criterion, which limits particles in the 5 to 15 μm bin to ≤ 50 particles/mL for at least 95 percent of the measurements during an individual filter run (see Section 1.4 for the water treatment goals).

This criterion was established based on individual filter runs, instead of the aggregate data set, because as a pilot facility, there may be anomalous filter runs that would artificially skew the aggregate dataset. Therefore, the data presented in the particle count tables in this report (such as Table 4-3) represent an average of the specified percentile from each individual filter run conducted during the test condition.

Because of the difficulty in proving treatment effectiveness when raw water particle counts are low, the particle count tables in this report only present average log removals from paired data (based on hydraulic residence time between raw water particle count and filter effluent particle count sample locations) when then raw water exceeds 500 counts/mL. This criterion is still quite stringent, considering that a raw water particle count of 500 counts/mL requires a filter effluent particle count ≤ 5 counts/mL to demonstrate 2-log removal. Therefore, statistics on the actual particle counts in the relevant size ranges (3 to 5 μm and 5 to 15 μm) are presented in the tables alongside the calculated log removal. If there were insufficient raw water particles in the relevant size ranges, log removals are presented as "NA".

Table 4-3. Raw water and filter effluent particle counts summary, averaged by individual runs conducted during the side-by-side testing of alum and PACI with no filter aid, from July 30 – August 5

Parameter		Raw Water		Train 1: PACI			Train 2: Alum		
				F6–Anth–72			F1–Anth–72		
		50th Percentile	95th Percentile	50th Percentile	95th Percentile	Log Removal [†]	50th Percentile	95th Percentile	Log Removal [†]
Turbidity (NTU)		0.34	0.36	0.07	0.10		NA	NA	
Particles (counts/mL)	3 to 5 µm	579	618	76	113	0.9	NA	NA	NA
	5 to 15 µm	445	478	64	99	0.9	NA	NA	NA

Parameter		F5–Anth–60			F2–GAC–60		
		50th Percentile	95th Percentile	Log Removal [†]	50th Percentile	95th Percentile	Log Removal [†]
Turbidity (NTU)			0.06	0.09		NA	NA
Particles (counts/mL)	3 to 5 µm		16	48		NA	NA
	5 to 15 µm		16	51		NA	NA

Parameter		F4–GAC–72			F3–GAC–72		
		50th Percentile	95th Percentile	Log Removal [†]	50th Percentile	95th Percentile	Log Removal [†]
Turbidity (NTU)			0.05	0.09		0.07	0.87
Particles (counts/mL)	3 to 5 µm		55	99		39	68
	5 to 15 µm		50	90		34	64

[†] Log removals calculated based the difference between the median raw water and median filter effluent particle counts in the specified size bin.

From Table 4-3 it can be seen that none of the filters achieved the performance goal of a 95th percentile ≤ 50 particles/mL in the 5 – 15 μm size range. The closest was Filter 5, which barely exceeded 50 particles/mL in the 5 – 15 μm size range, and was just under 50 particles/mL in the 3 – 5 μm size range. This, along with the inconsistency in filter UFRVs seen in Figure 4-21, suggests that filter aid polymer is required for effective treatment of this source water.

Additional Testing with Filter Aid

Following the relatively poor performance described in the preceding section, the decision was made to switch back to filter aid polymer for additional side-by-side testing. These additional runs, conducted from August 5 to 12, are presented in Figure 4-23.

Compared to the initial period of higher filtration rate testing, the runs conducted from August 5 to 12 were less consistent. However, similar trends hold; the PACI filters tended to have higher UFRVs than the corresponding alum filters.

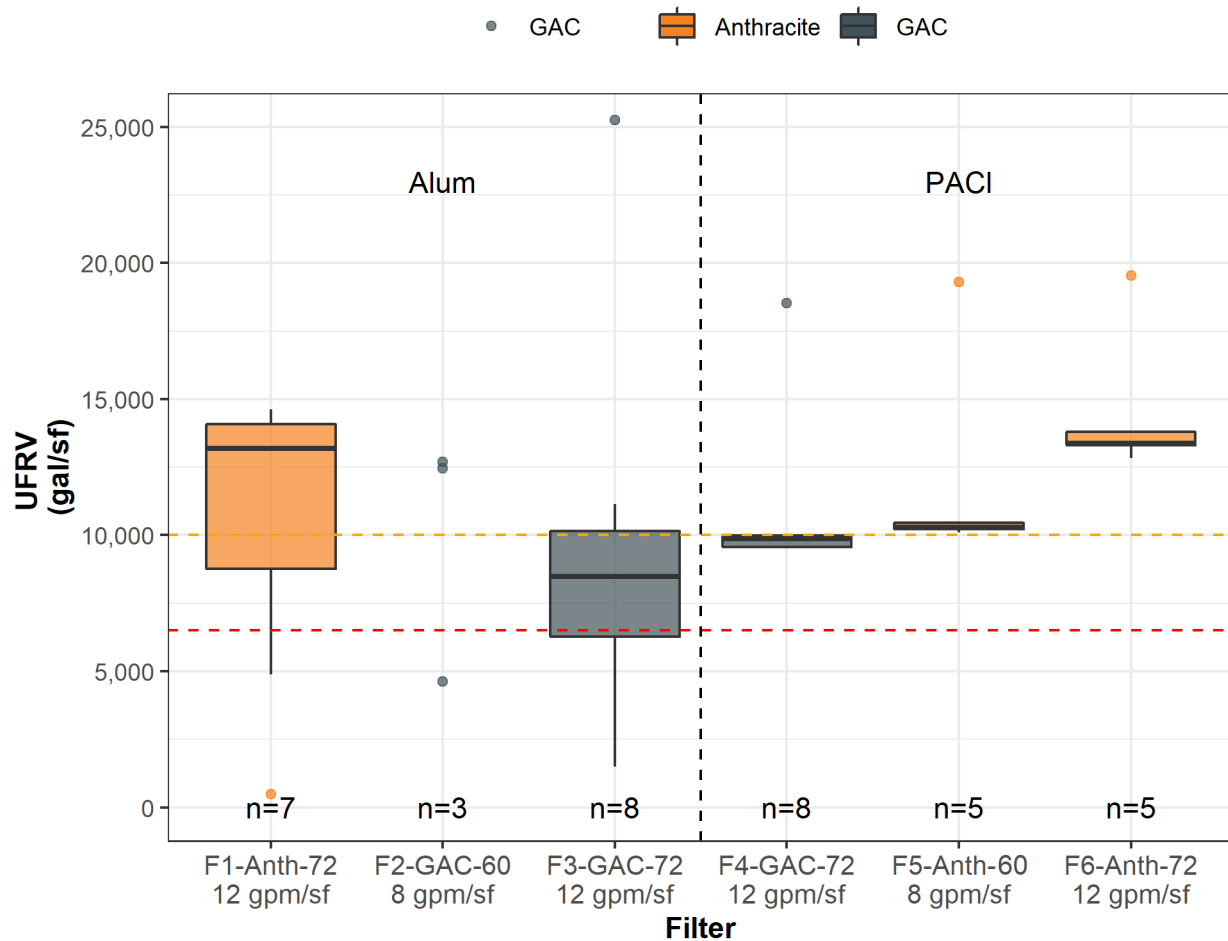


Figure 4-23. Calculated UFRVs during side-by-side testing of alum and PACI with filter aid, from August 5 –12

Figure 4-24 summarizes the corresponding filter effluent turbidity data recorded during the filter runs shown in Figure 4-23. Overall, filter effluent turbidities were quite good, with median effluent turbidities at or below 0.05 NTU for all filters. The train with PACI pre-treatment was produced particularly low filter effluent turbidities.

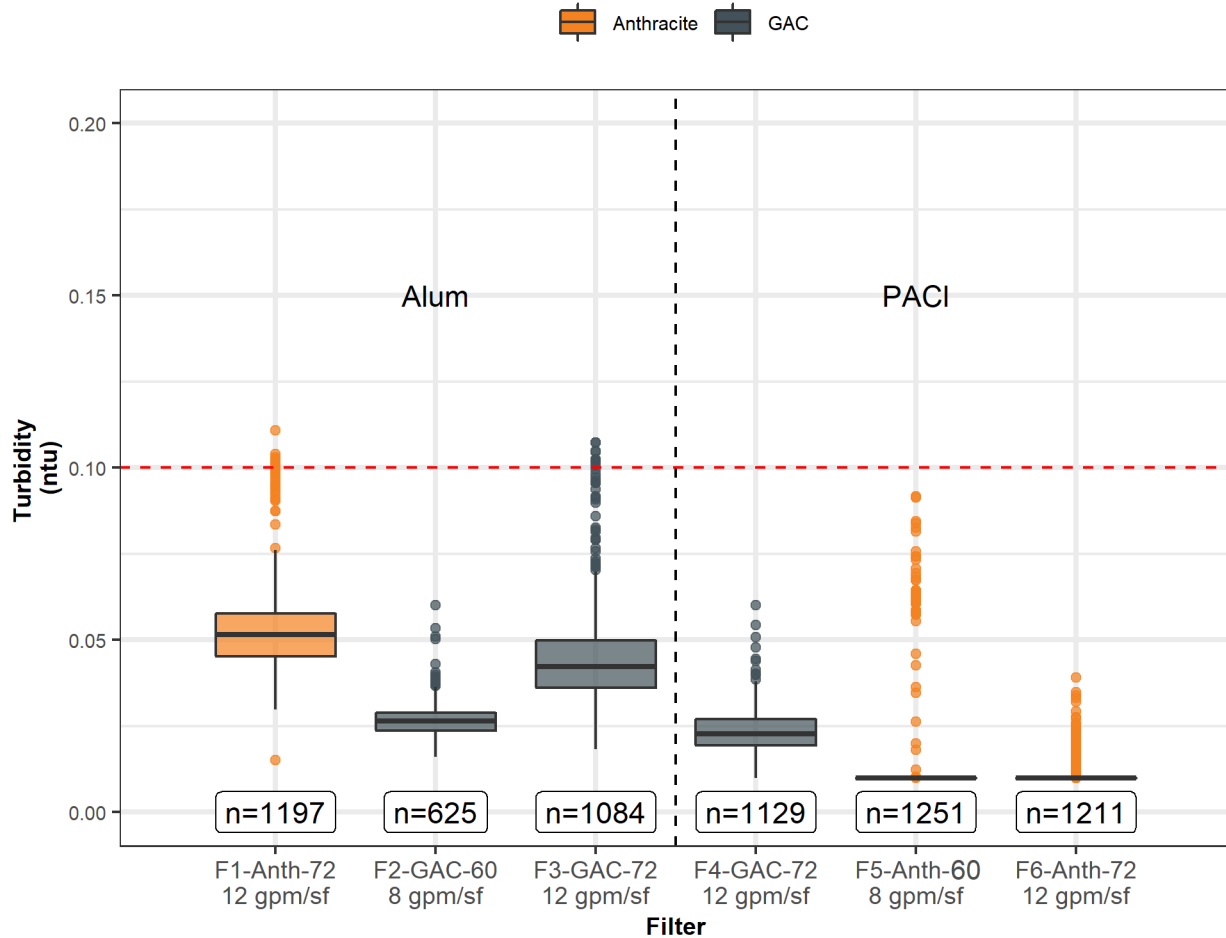


Figure 4-24. Filter effluent turbidities recorded during accepted filter runs during the side-by-side testing of alum and PACI with filter aid, from August 5 –12

A summary of the particle count data collected during this test period, from August 5 to 8, excluding the period from August 5 to 12 when operations were inconsistent, is presented in Table 4-4. Compared to the preceding test period, filter effluent particle counts are significantly lower, further supporting the benefit of filter aid polymer on filter performance. Raw water particle counts were quite low during this test period, so even though all of the filters except for Filter 3 generally maintained single-digit filter effluent particle counts, none of the 72-inch filters operating at 12 gpm/sf could demonstrate 2-log particle removal in either of the relevant size ranges. Nonetheless, five of the filters (all but Filter 2) maintained particle counts in the relevant size ranges, on average, below 50 counts/mL for at least 95 percent of their runtime.

Table 4-4. Raw water and filter effluent particle counts summary, averaged by individual runs conducted during the side-by-side testing of alum and PACI with filter aid, from August 5 –12

Parameter		Raw Water		Train 1: PACI			Train 2: Alum		
				F6–Anth–72			F1–Anth–72		
		50th Percentile	95th Percentile	50th Percentile	95th Percentile	Log Removal [†]	50th Percentile	95th Percentile	Log Removal [†]
Turbidity (NTU)		0.45	0.49	0.01	0.01		0.05	0.07	
Particles (counts/mL)	3 to 5 µm	537	592	6	7	2.0	7	14	1.9
	5 to 15 µm	407	464	3	4	2.1	5	13	1.9

Parameter		F5–Anth–60			F2–GAC–60		
		50th Percentile	95th Percentile	Log Removal [†]	50th Percentile	95th Percentile	Log Removal [†]
Turbidity (NTU)			0.01	0.02		0.03	0.05
Particles (counts/mL)	3 to 5 µm		4	6	2.1	4	28
	5 to 15 µm		2	3	2.3	1	54

Parameter		F4–GAC–72			F3–GAC–72		
		50th Percentile	95th Percentile	Log Removal [†]	50th Percentile	95th Percentile	Log Removal [†]
Turbidity (NTU)			0.02	0.03		0.06	0.08
Particles (counts/mL)	3 to 5 µm		6	10	2.0	20	29
	5 to 15 µm		3	12	2.1	30	43

[†] Log removals calculated based the difference between the median raw water and median filter effluent particle counts in the specified size bin.

Evaluation of Coagulant Performance with Pre-oxidation

The final coagulant selection test evaluated alum and PACl side-by-side with pre-oxidation using ozone. The goal for this test was to determine if one coagulant was more effective when the raw water organics were transformed via pre-oxidation. This testing was conducted from August 20 to 30, during which both trains received water that had been pre-oxidized with an applied ozone dose of 0.5 mg/L.

Pre-oxidation significantly improved filter UFRVs, as shown in Figure 4-25. Except for one run on Filter 1, all filters exceeded 10,000 gal/sf-run including Filter 3 (GAC, 12 gpm/sf), which saw UFRVs more than double from the preceding test period. In general, the UFRVs were higher in the filters receiving water treated with alum when compared to the filters treated with PACl, although performance in the deeper anthracite filters operating at 12 gpm/sf was similar.

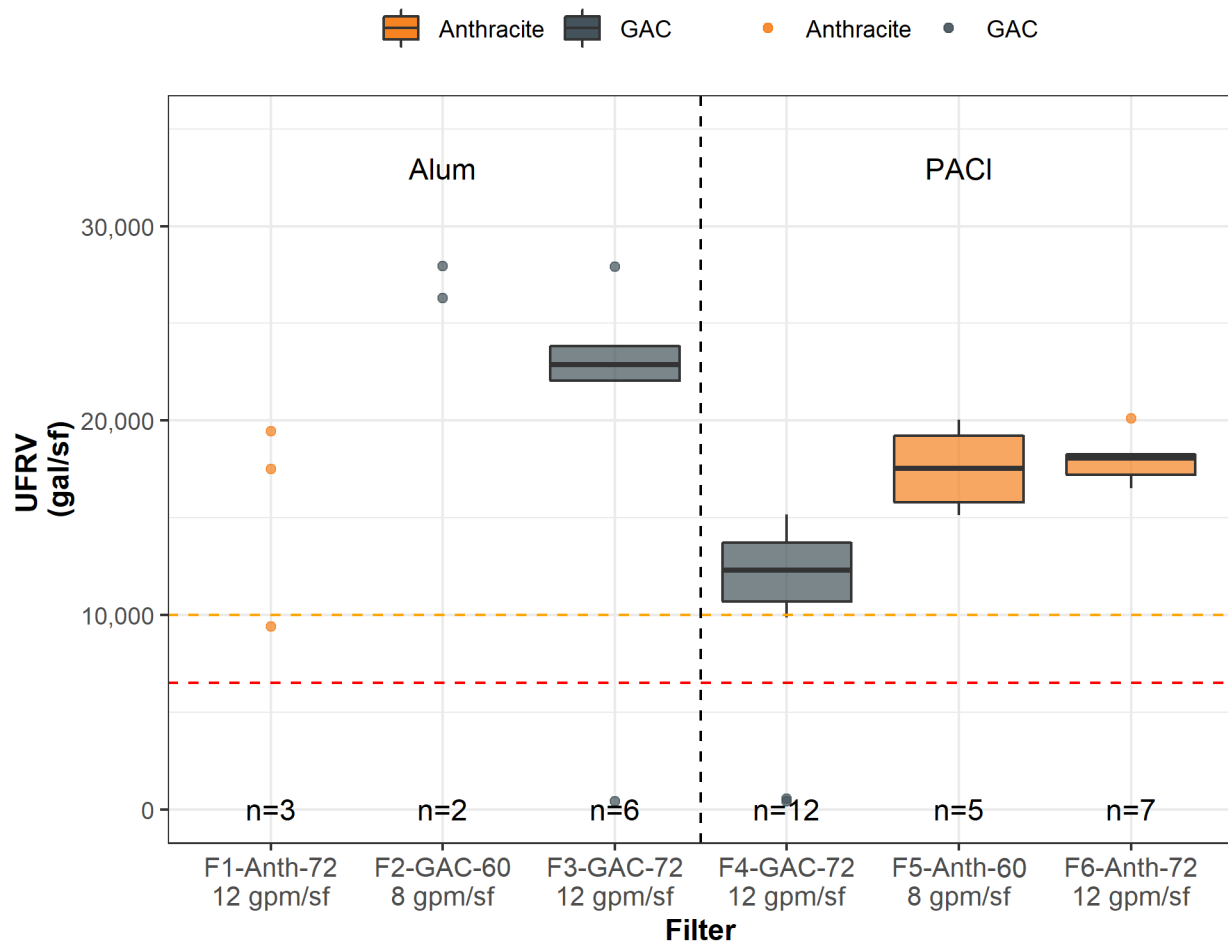


Figure 4-25. Calculated UFRVs during side-by-side testing of alum and PACl following ozone pre-oxidation, conducted August 20 –30

Filter effluent turbidities recorded during the accepted runs during this period are shown in Figure 4-26. Filters 2 through 6 generally produced lower turbidity water, with median filter effluent turbidities near or below 0.03 NTU. Filter 1 had consistently higher filter effluent turbidities, with a median near 0.08 NTU.

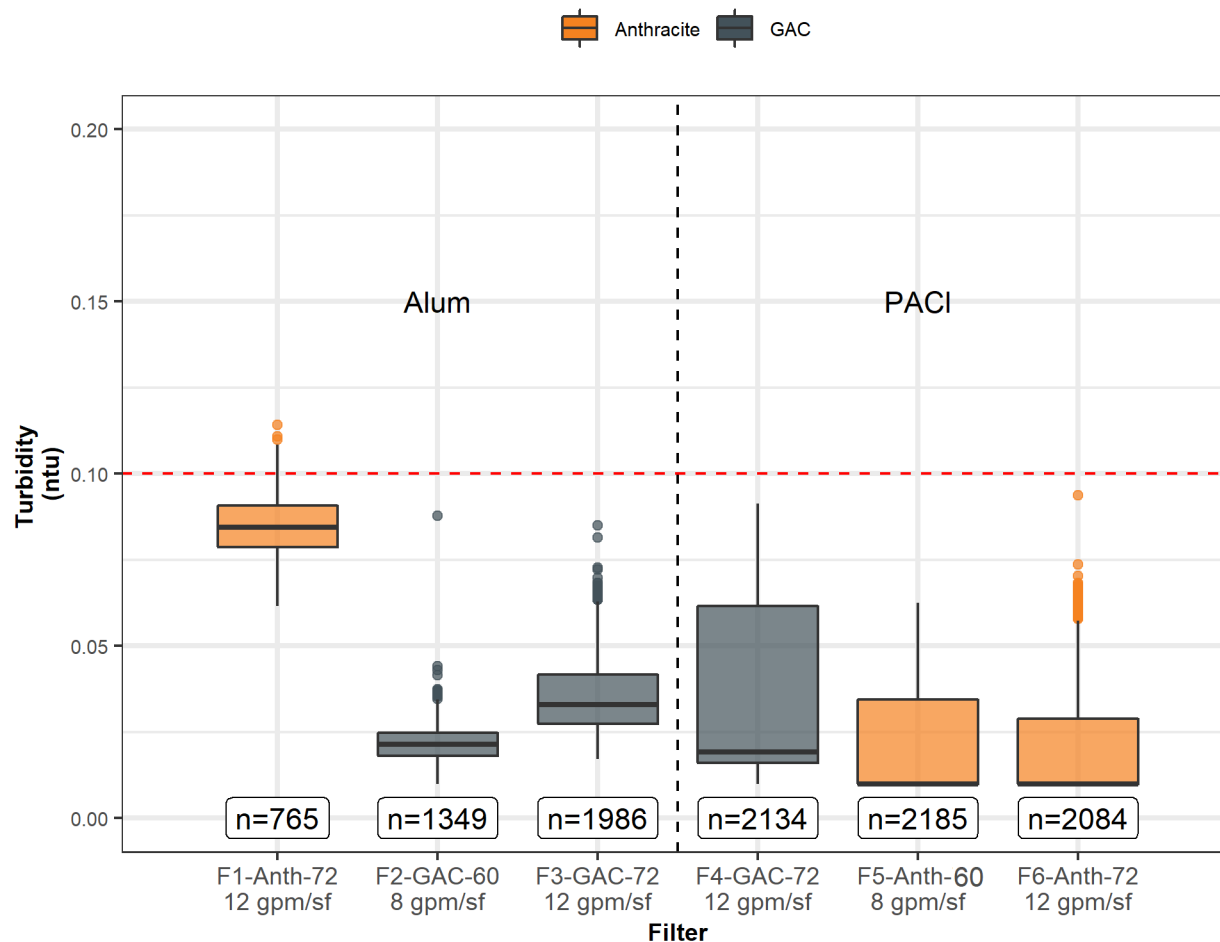


Figure 4-26. Filter effluent turbidities recorded during accepted filter runs during side-by-side testing of alum and PACI following ozone pre-oxidation, conducted August 20 – 30

Particle count data collected during this test period are summarized in Table 4-5. Particle counts out of the 12 gpm/sf filters (Filters 1, 3, 4, and 6) were generally higher, with only Filters 4 and 5 having 95th percentile particle counts in the single digits. However, all six filters met the performance target of ≤ 50 particles/mL in the 5 to 15 μm range. Raw water particle counts were particularly low during this test period, so log removals were not be calculated for most filters. Those filters that did operate when raw water particle counts were above 500 counts/mL generally demonstrated >2-log removal of particles.

Table 4-5. Raw water and filter effluent particle counts summary, averaged by accepted filter runs during side-by-side testing of alum and PACI following ozone pre-oxidation, conducted August 20 – 30

Parameter		Raw Water		Train 1: PACI			Train 2: Alum		
				F6–Anth–72			F1–Anth–72		
		50th Percentile	95th Percentile	50th Percentile	95th Percentile	Log Removal [†]	50th Percentile	95th Percentile	Log Removal [†]
Turbidity (NTU)		0.39	0.40	0.03	0.04		0.09	0.10	
Particles (counts/mL)	3 to 5 µm	371	376	15	29	1.4	8	28	1.7
	5 to 15 µm	169	172	13	25	1.1	7	26	1.4

Parameter		F5–Anth–60			F2–GAC–60		
		50th Percentile	95th Percentile	Log Removal [†]	50th Percentile	95th Percentile	Log Removal [†]
Turbidity (NTU)		0.03	0.03		0.02	0.03	
Particles (counts/mL)	3 to 5 µm	7	8	1.7	1	3	2.6
	5 to 15 µm	3	3	1.8	3	7	1.8

Parameter		F4–GAC–72			F3–GAC–72		
		50th Percentile	95th Percentile	Log Removal [†]	50th Percentile	95th Percentile	Log Removal [†]
Turbidity (NTU)		0.06	0.07		0.03	0.05	
Particles (counts/mL)	3 to 5 µm	4	5	2.0	12	29	1.5
	5 to 15 µm	3	4	1.8	14	43	1.1

[†] Log removals calculated based on the difference between the median raw water and median filter effluent particle counts in the specified size bin.

Organics Removal for Side-by-Side Comparison

Organics removal between the alum and PACl trains were comparable on average between the side-by-side comparison testing, with slight differences in percent removals for the initial testing with low filtration rates and during the high filtration rate testing.

Figure 4-27 through Figure 4-32 show the TOC, UV₂₅₄, and color data through the alum and PACl side-by-side comparison period from July 16 to August 30. Organics removal between the alum and PACl trains were comparable on average through the side-by-side comparison testing until pre-ozonation was applied, which resulted in a larger TOC removal with PACl than alum. As mentioned previously, for TOC samples less than the MRL, the value was reported as half the MRL (0.15 mg/L). In addition, color data were also corrected for the MRL, with values less than 3 reported as half the MRL (1.5).

Initially, TOC was removed to below the MRL for the GAC filters in both trains. The anthracite filters removed TOC by about 50 percent in the alum fed train and by 40 percent in the PACl fed train. After filter aid was stopped, and coagulant aid dosing of 0.25 mg/L started on July 30, there was an increase in TOC in the GAC filters with a larger increase in the train with alum. When filter aid was added again on August 5, TOC reduced back to below the MRL for the GAC filter and UV₂₅₄ reduced for all filters, demonstrating the benefit of filter aid addition to improve filterability. All color was measured below the MRL for all filters throughout testing with a few exceptions. A color measurement of 9 Pt-Co units on August 2 from the GAC filter effluent (Filter 4) may have been an instrument error and doesn't indicate a real change in the filter performance. The color measure of 4 Pt-Co units on August 21 in Filter 6 from the PACl train corresponds to an increase in UV₂₅₄ around the same time and, therefore, is considered to represent an actual change in filter effluent organics (as compared to an instrumentation artifact). After pre-ozonation treatment was initiated in both trains on August 20, the TOC in the alum train filter effluent increased, resulting in a lower percent removal in the alum train (45 percent) compared to the PACl train (58 percent). UV₂₅₄ removals were approximately 81 percent and 85 percent for the alum and PACl trains, respectively. Color was removed to below the MRL on average in the alum train for all filters with a removal of >80 percent, while the average color removal for the PACl train was about 66 percent with all values above the MRL.

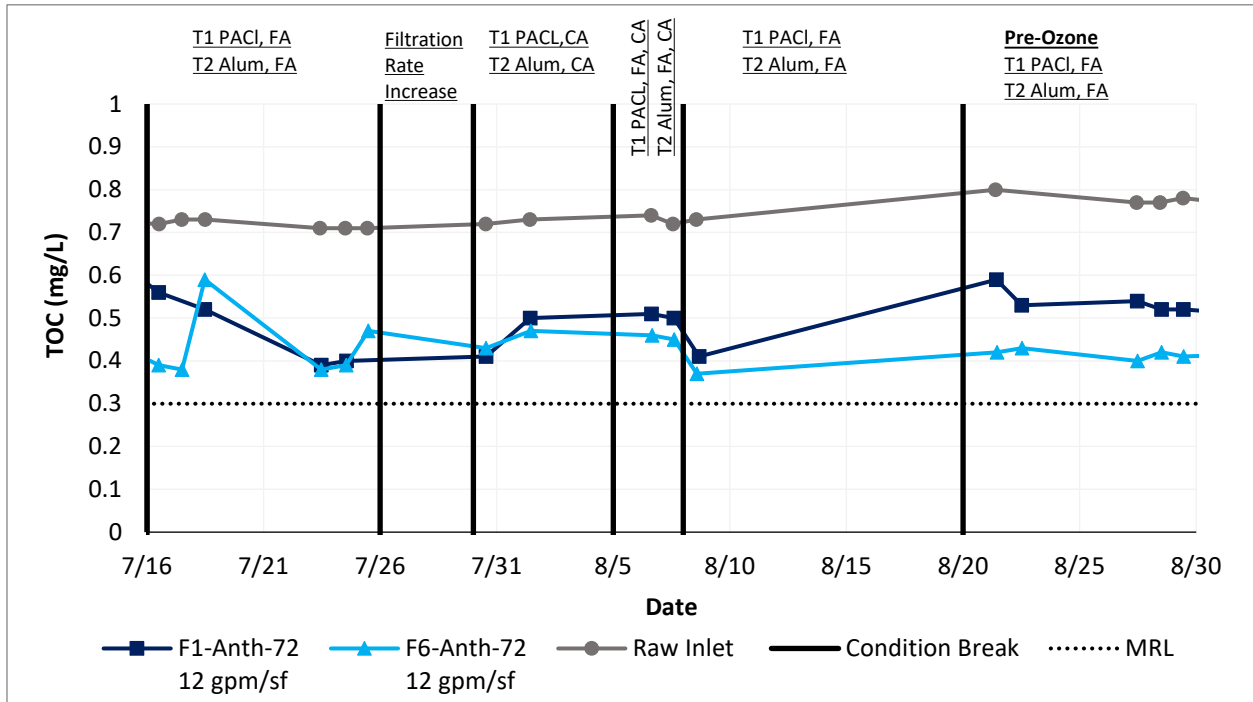


Figure 4-27. Organics removal for Filters 1 and 6—alum vs PACl: TOC

TOC in Filter 1 (Train 2 [T2] - alum) and Filter 6 (Train 1 [T1] - PACl) effluent during the side-by-side testing of alum and PACl from July 16 – August 30. Abbreviations: FA = Filter Aid, CA= Coagulant Aid.

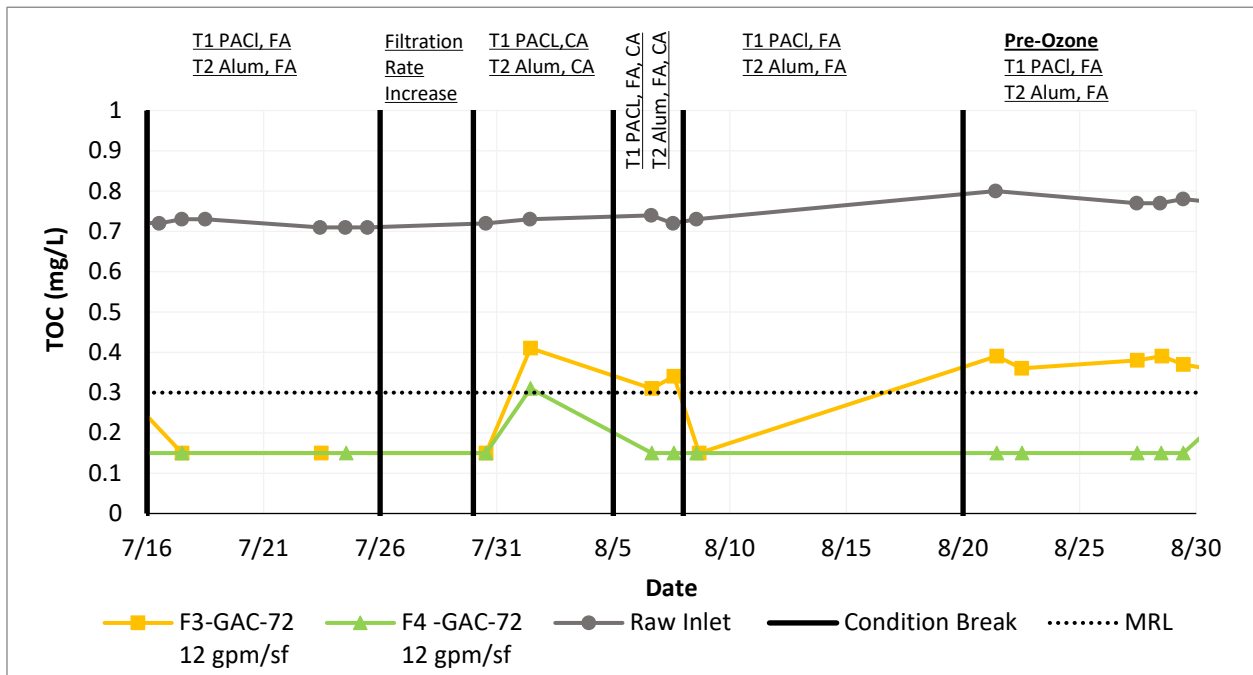


Figure 4-28. Organics removal for Filters 3 and 4—alum vs PACl: TOC

TOC in Filter 3 (Train 2 [T2] - alum) and Filter 4 (Train 1 [T1] - PACl) effluent during the side-by-side testing of alum and PACl from July 16 – August 30. Abbreviations: FA = Filter Aid, CA= Coagulant Aid.

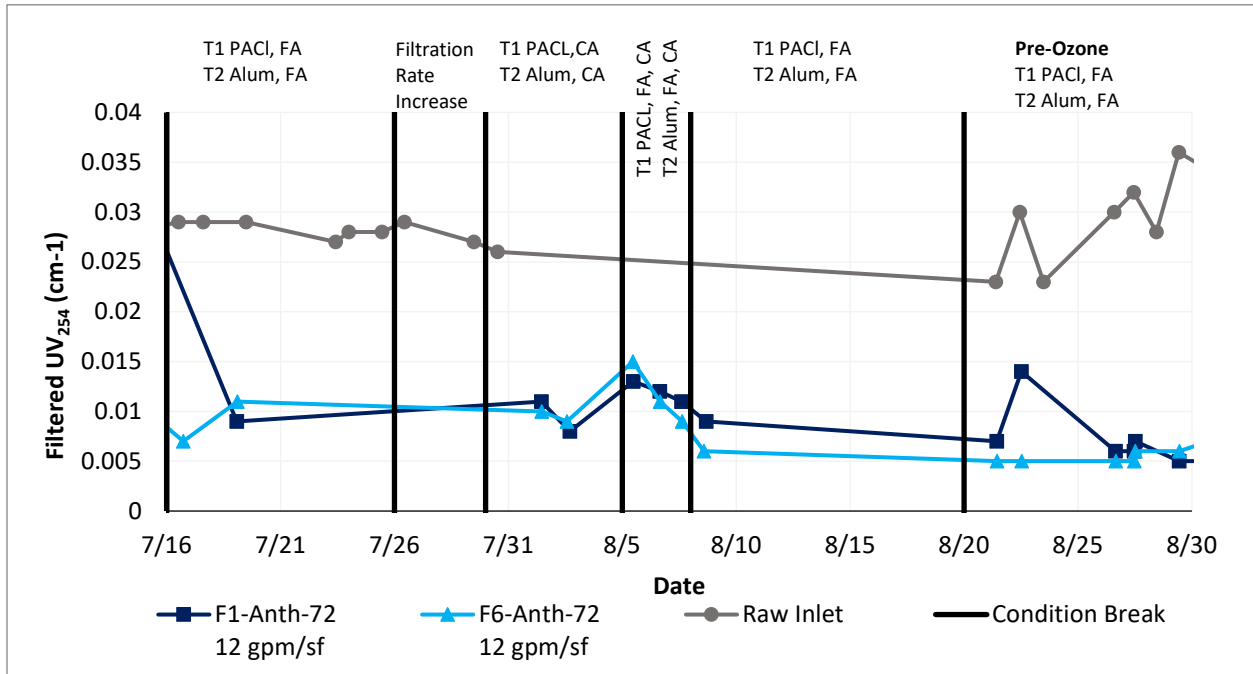


Figure 4-29. Organics removal for Filters 1 and 6 –alum vs PACl: filtered UV₂₅₄

Filtered UV₂₅₄ in Filter 1 (Train 2 [T2] - alum) and Filter 6 (Train 1 [T1] - PACl) effluent during the side-by-side testing of alum and PACl from July 16 – August 30. Abbreviations: FA = Filter Aid, CA= Coagulant Aid.

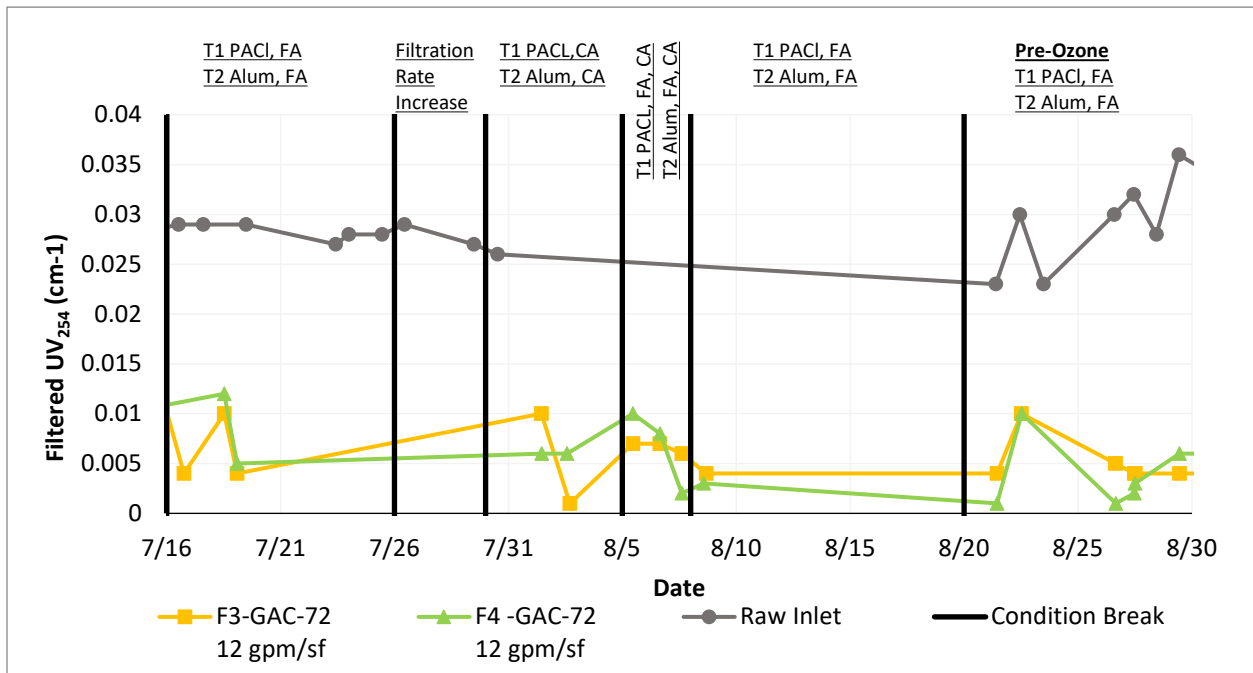


Figure 4-30. Organics removal for Filters 3 and 4 –alum vs PACl: filtered UV₂₅₄

Filtered UV₂₅₄ in Filter 3 (Train 2 [T2]- alum) and Filter 4 (Train 1[T1]- PACl) effluent during the side-by-side testing of alum and PACl at high filtration rates from July 16 – August 30. Abbreviations: FA = Filter Aid, CA= Coagulant Aid.

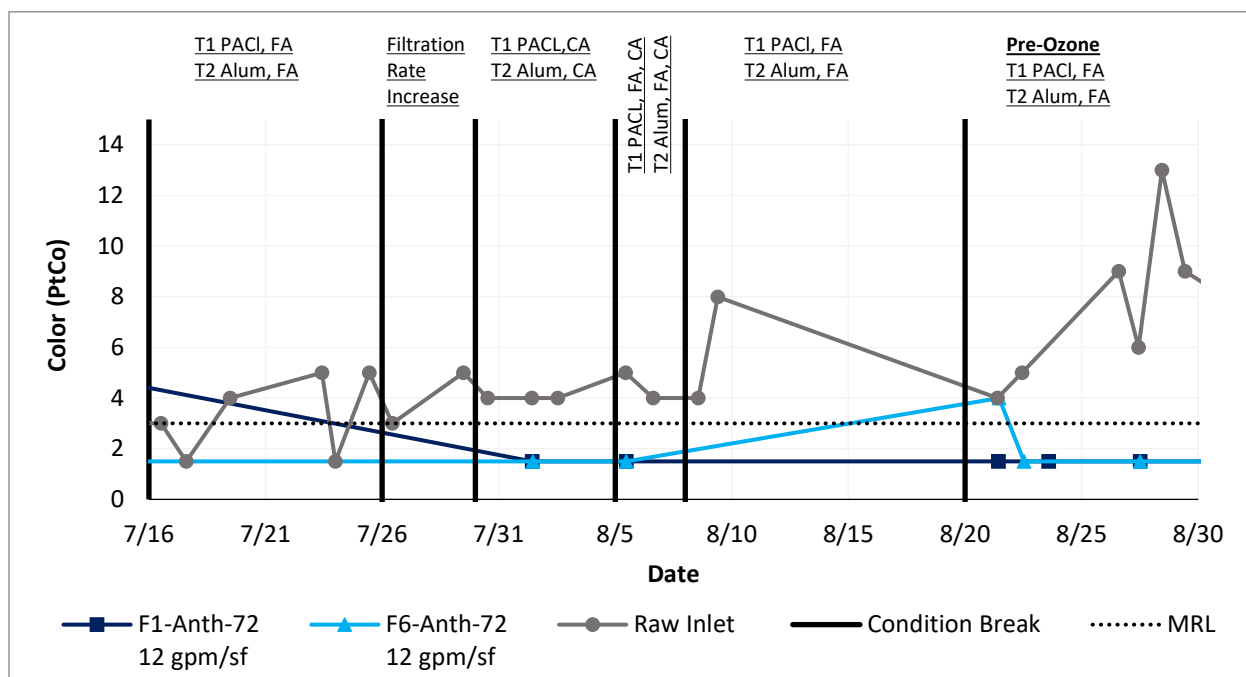


Figure 4-31. Organics removal for Filters 1 and 6—alum vs PACI: Apparent color

Apparent Color in Filter 1 (Train 2 [T2] - alum) and Filter 6 (Train 1 [T1] - PACI) effluent during the side-by-side testing of alum and PACI from July 16 – August 30. Abbreviations: FA = Filter Aid, CA= Coagulant Aid.

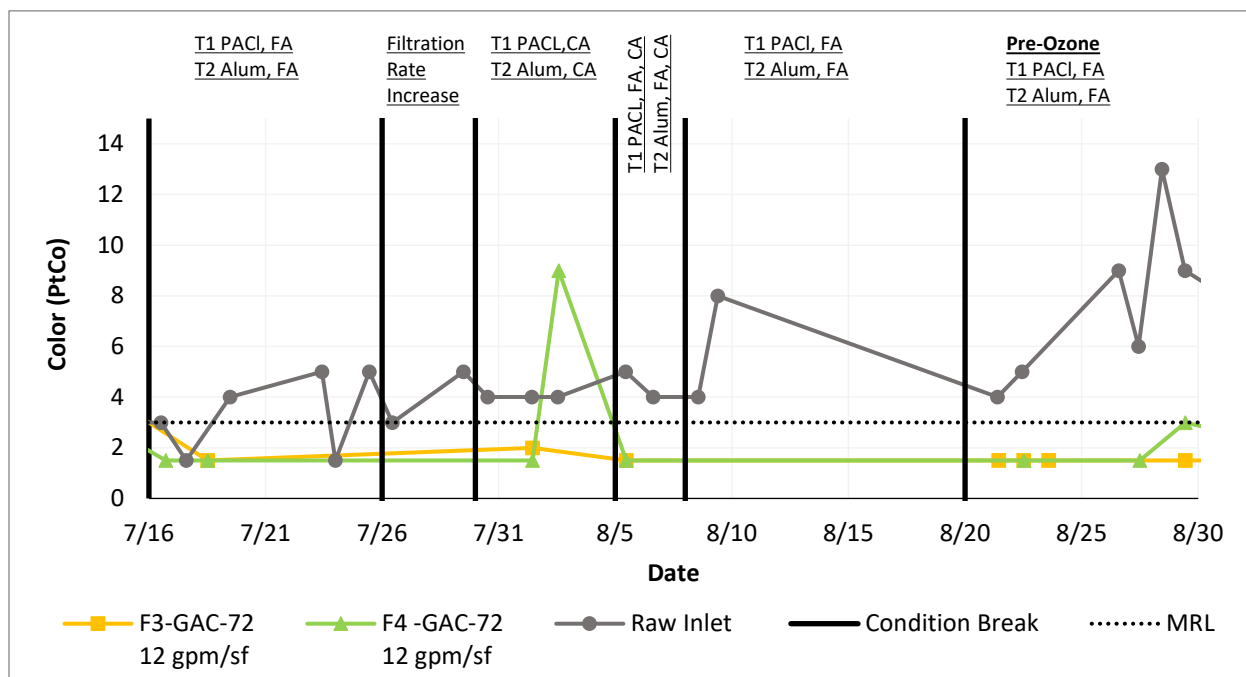


Figure 4-32. Organics removal for Filters 3 and 4—alum vs PACI: Apparent color

Apparent Color in Filter 3 (Train 2 [T2] - alum) and Filter 4 (Train 1 [T1] - PACI) effluent during the side-by-side testing of alum and PACI from July 16 – August 30. Abbreviations: FA = Filter Aid, CA= Coagulant Aid.

4.2.3 Summary of Pilot Coagulant Comparison–Summer/Fall Season

Based on initial coagulant screening, alum and PACl demonstrated adequate performance while ACH and ferric were difficult to find conditions that met the pilot water treatment goals. More extensive side-by-side evaluations of alum and PACl were conducted. Filtration rates were increased to 12 gpm/sf in the deeper filters (8 gpm/sf in the shorter filters) without any adverse impact on performance.

In general, there was no clear performance difference between alum and PACl. Filter productivity was slightly higher with PACl when pre-oxidation was not applied, and somewhat higher with alum when pre-oxidation was implemented (the GAC filter columns saw an increase in UFRVs, but the anthracite column did not). Organics removal shows an opposite trend, with an increase in TOC in the alum fed trains with pre-oxidation applied. With both coagulants, filter productivity and filter effluent particle counts met performance goals, provided that filter aid polymer was also used. Without filter aid polymer, neither coagulant was capable of meeting filter effluent particle count goals. Overall, organics removal was comparable between the two trains through the testing period with neither coagulant performing significantly better than the other for all organics parameters evaluated (i.e., TOC, UV₂₅₄, and color).

Based on these initial results, the decision was made to use PACl as the primary coagulant during fall testing. This decision was made primarily on operational grounds; while performance was similar between both alum and PACl, alum required more careful monitoring of raw water alkalinity and required feeding supplemental alkalinity (in the form of sodium bicarbonate) at higher alum doses. Since PACl is less sensitive to alkalinity, it is easier to maintain PACl coagulation at the pilot.

4.3 Pre-oxidant Testing

This section describes the results from pre-ozonation and pre-chlorination testing. It also includes bench-scale ozonation testing to determine ozone demand/decay characteristics to inform the ozone module operating conditions.

4.3.1 Ozone Kinetics

The following sections discuss ozone kinetics from bench-scale testing, and at the pilot scale to inform ozone dose and contact time criteria.

4.3.1.1 Bench-scale Testing

Bench-scale ozonation demand-decay testing was conducted on Portland Bull Run surface water at the University of Colorado (CU) Boulder SEEL Laboratory by CU and BC to understand ozone decay rates and ozone demand for the water source, and to help inform initial operation conditions for the ozone module. The full report is provided in Appendix B. Water samples from Portland Bull Run surface water, collected on March 1, 2019, were stored at the CU laboratory until the ozone demand-decay testing on April 2, 2019. Sample water was ozonated using the batch aqueous stock solution method described in *Standard Methods for the Examination of Water and Wastewater 22nd edition* 2350 D. Aqueous ozone concentrations were measured using the direct UV method at 260 nm wavelength and dosed at four target applied ozone doses of 0.5, 1.0, 1.5, and 2.0 mg/L. Ozone residuals were analyzed using Hach ozone reagent AccuVac ampules at multiple detention times.

Figure 4-33 shows the ozone residual over time at the different applied ozone doses, as well as the reaction rates, which decrease with increased applied dose. The difference between the applied ozone dose and ozone residual, measured at 30 seconds, was identified as the instantaneous ozone demand. On average, the instantaneous ozone demand was 0.43 mg/L O_3 . In addition, ozone residual was measurable at greater than 65 minutes for higher ozone doses (1.5 and 2.0 mg/L) where there was not sufficient ozone demand.

Water quality parameters of DOC, TOC, $UV_{200-800}$, and apparent color were measured throughout the testing to evaluate the transformation of organic compounds and potential impacts on DBP precursors. Ozone did not impact TOC and DOC concentrations or pH. UV_{254} and apparent color on the other hand were significantly reduced with increased ozone dose.

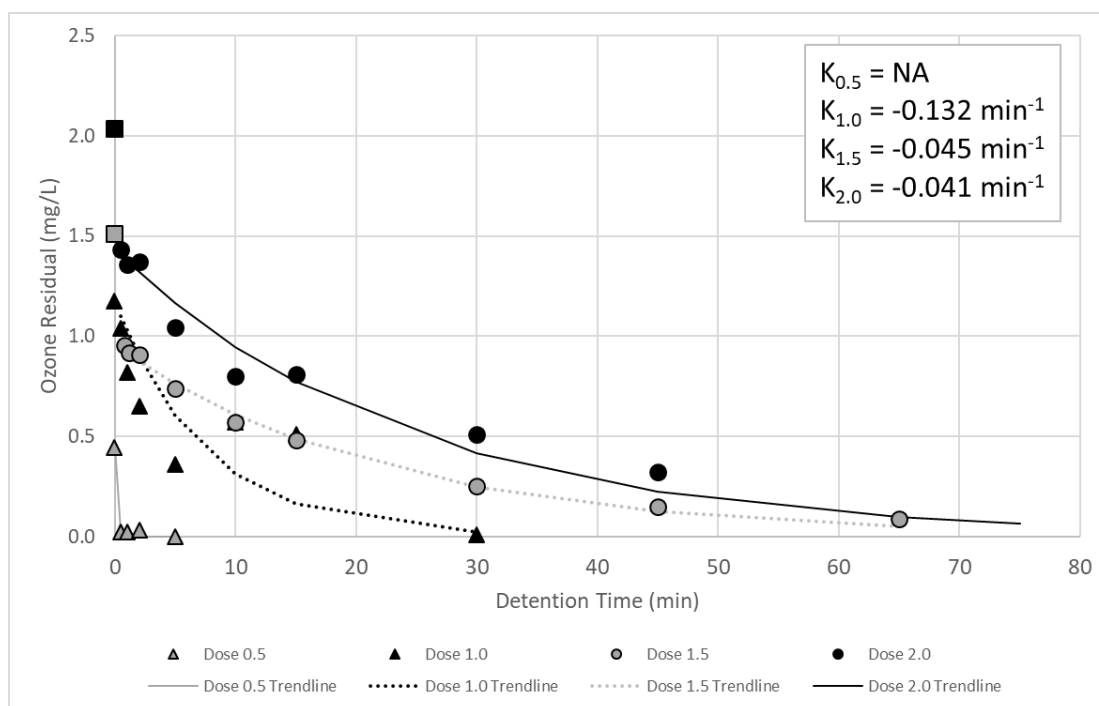


Figure 4-33. Ozone residual over time

*Figure from Bench-Scale Ozone Demand-Decay Testing Report
BC, May 2019, see Appendix B*

4.3.1.2 Pilot-scale Ozone Demand and Decay

An ozone residual demand and decay curve as a function of nominal detention time was developed from ozone residual operational data when ozone was dosed between 0.5 and 1.0 mg/L O_3 for Train 1 and Train 2 (Figure 4-34). A boxplot of Train 2 with a dual fit rate constant overlaid is also presented (Figure 4-35). The nominal detention time was calculated based on a constant flow rate of 9.5 gpm and information on the geometry of the ozone contactor. It was confirmed that using the exact instantaneous flow rate signal data for computing detention time did not make a substantial difference in the outcome of this analysis due to small changes in the flowrate so the nominal preselected constant flow rate was used for the calculation. The transferred dose was used for the ozone concentration at detention time zero. Train 1 has a more limited data set than Train 2. This is because during the period of data collection for ozone decay analysis Train 1 was primarily operated without ozone to compare and contrast the effect of pre-ozonation for overall pilot scale operations.

The ozone residual curve for the target dose of 1.0 mg/L O₃ from the bench-scale test in the section above (Figure 4-33) is similar in general shape to the pilot-scale ozone residual curves. The decay rate constant was two times greater than the initial decay observed in the bench-scale curves (for a 1 mg/L dose using a first order decay fit). This is likely due to the difference in the seasonality of the samples. The bench scale tests were taken in March and the pilot scale evaluation occurred during the month of October when more organics were present in the water, which consumed a greater amount of ozone.

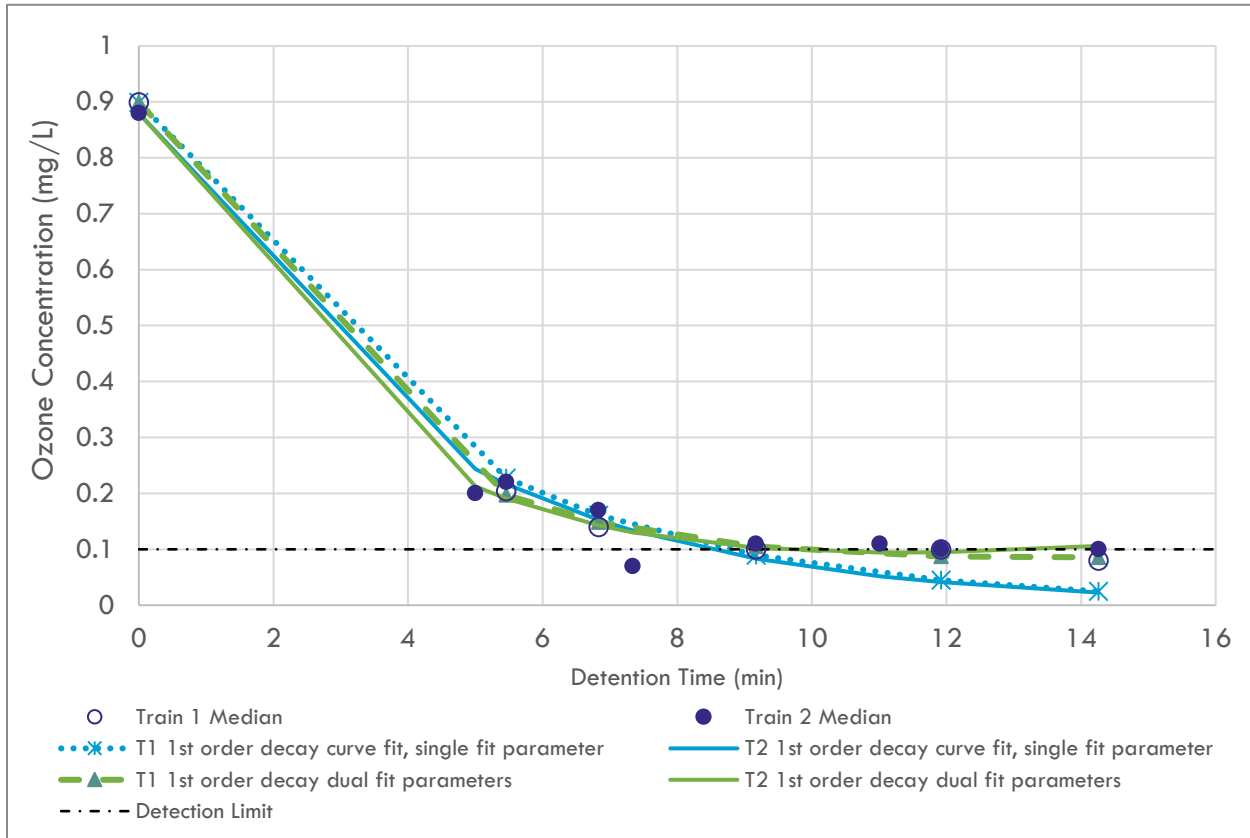


Figure 4-34. Pilot-scale ozone residual curve for Train 1 and Train 2, Ozone Dose of 1 mg/L (T1)

Points shown at time t=0 are the calculated transfer dose, not an observed ozone residual

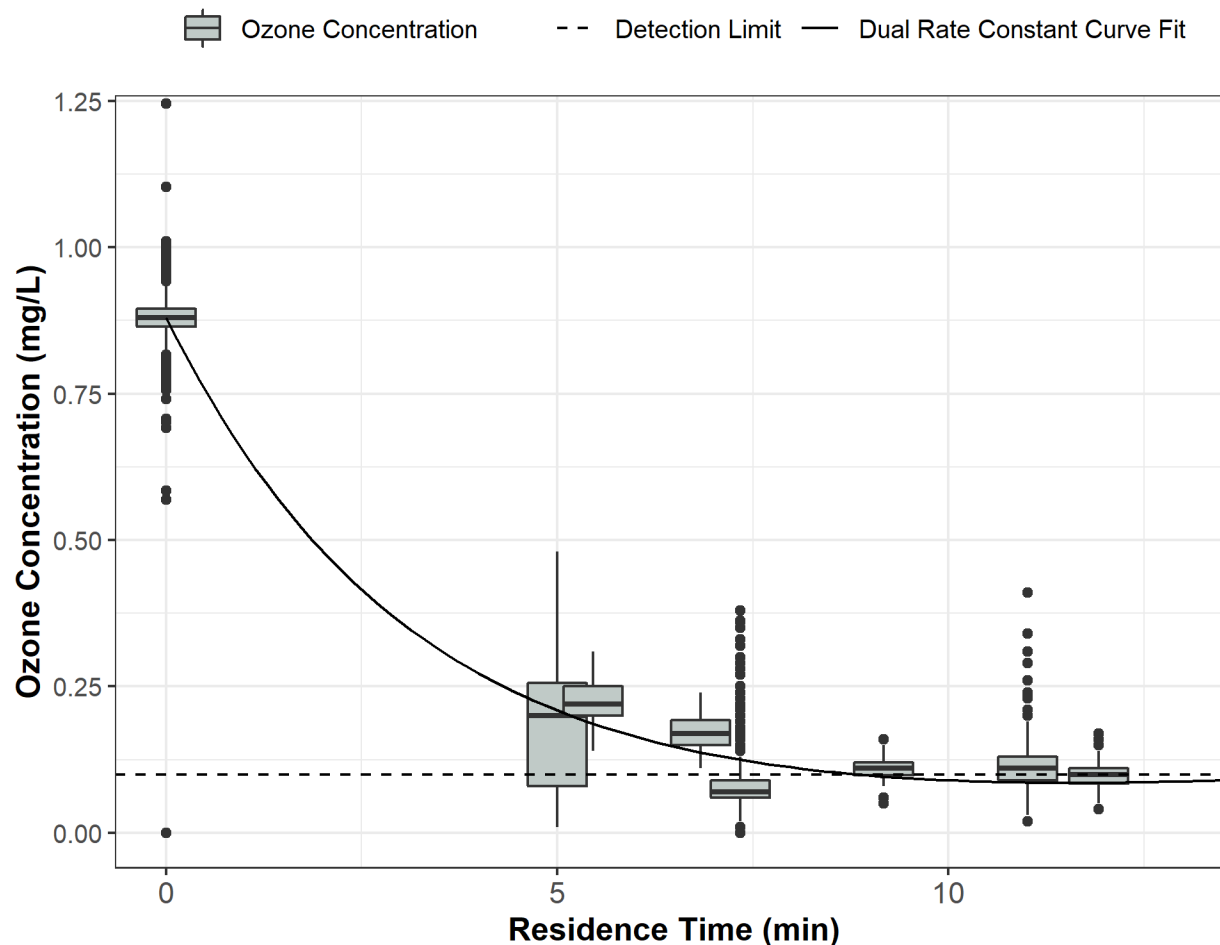


Figure 4-35. Boxplot of ozone residual curve for Train 2, Ozone Dose of 1 mg/L (T2)

Ozone decay and decay kinetics were determined assuming using first order decay kinetics. The kinetics were compared between Train 1 and Train 2 for both single and split rate constants (Table 4-6). The rate constants were not adjusted for temperature effects. The calculated rate constants were similar for both Train 1 and Trains 2 curves despite the variance the larger sample size caused for Train 2. The R^2 indicated a good correlation for both curve fits with slightly higher correlation for a split rate constant. These values are described in Table 4-6 below.

Table 4-6. Pilot-scale Ozone Decay Kinetics ^(a)

Parameter	Variable	Train 1	Train 2
Single Fit Constant ^(b)	1 st Order Decay (k)	0.25	0.26
	R ²	0.98	0.98
Dual Rate Constant ^(c)	High Rate (k _h)	0.32	0.32
	Low Rate (k _l)	0.04	0.11
	A	0.95	0.97
	R ² ^(d)	0.99	0.99
Number of Samples		1,512	3,034

a. Temperatures ranged from 11°C to 15°C over the period of data collection.

b. 1st Order Single Fit Constant Equation: $C = C_0 e^{-kt}$, where t = time (min), C_0 = initial concentration (mg/L), C = final concentration (mg/L), k = decay constant (min⁻¹)

c. 1st Order Split Rate Constant Equation: $C = C_0 e^{-k_l t} + (1 - A)C_0 e^{-k_h t}$, where t = time (min), C_0 = initial concentration (mg/L), C = final concentration (mg/L), k_l and k_h = computed decay constants (min⁻¹), and A is a dimensionless value less than one that determines the regions of high and low rates.

d. R² values were evaluated using the sum of residual squares

4.3.2 Pre-ozonation vs No pre-oxidation

The first round of pre-oxidant testing compared conventional treatment without pre-oxidation in Train 1 to conventional treatment with pre-ozonation in Train 2, as shown in Figure 4-36. An applied ozone dose for Train 2 was initially set at 0.5 mg/L when this round of testing began on August 30. On September 18, the applied pre-ozone dose for Train 2 was increased to 1.0 mg/L, where it was maintained for the remainder of the scenario. At the beginning of the scenario, both trains were fed PACl at a nominal dose of 2.3 mg/L, along with 0.01 mg/L of filter aid polymer. On September 23, the PACl dose was increased to 3 mg/L based on SCM measurements to improve particle surface charge neutralization.

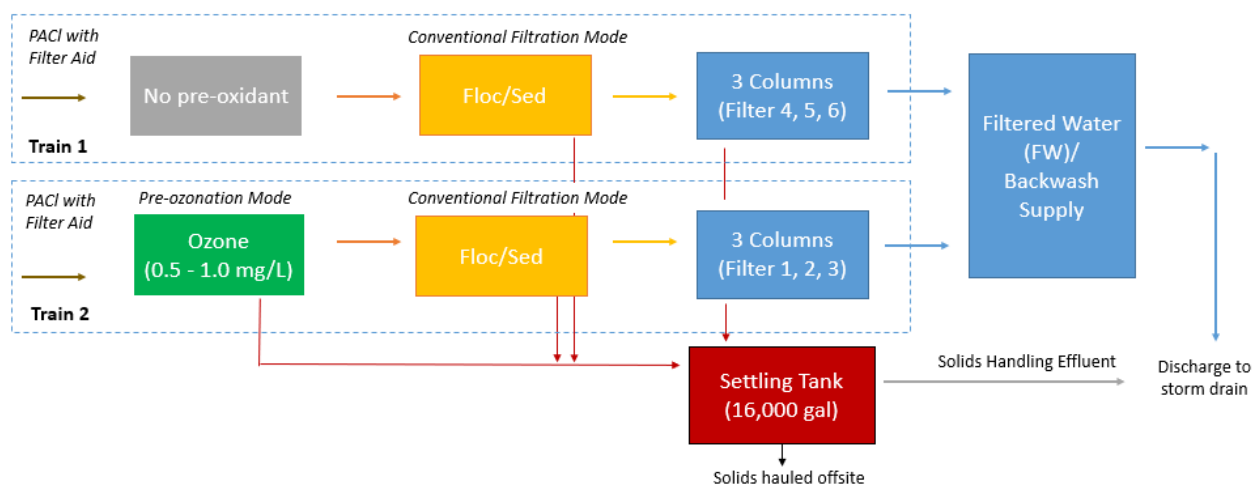


Figure 4-36. Treatment train for pre-ozonation treatment evaluation

This section describes filtration performance when testing pre-ozonation in Train 2 and no ozonation in Train 1. Compared to the coagulant evaluation, this test period was designed to evaluate the test condition for a longer period of time, resulting in a much more robust dataset.

The calculated UFRVs for this condition are presented in Figure 4-37. Overall, it is clear that pre-oxidation via ozone significantly improves filter productivity. For example, the ozonated anthracite filter with a loading rate of 12 gpm/sf (Filter 1) had a 50th percentile UFRV of approximately 18,000 gal/sf-run while the no pre-oxidant anthracite filter at the same loading rate had a 50th percentile UFRV of approximately 10,000 gal/sf-run. On average, the median UFRV for the pre-ozonated filters was 1.5 times greater than that of the no pre-oxidant filters. The UFRVs on both trains exceeded the goal of 6,500 gal/sf-run during 95 percent of the operational time. All of the filters' UFRV 50th percentiles were at or greater than 10,000 gal/sf-run. The filters receiving water treated with ozone significantly exceeded the performance target.

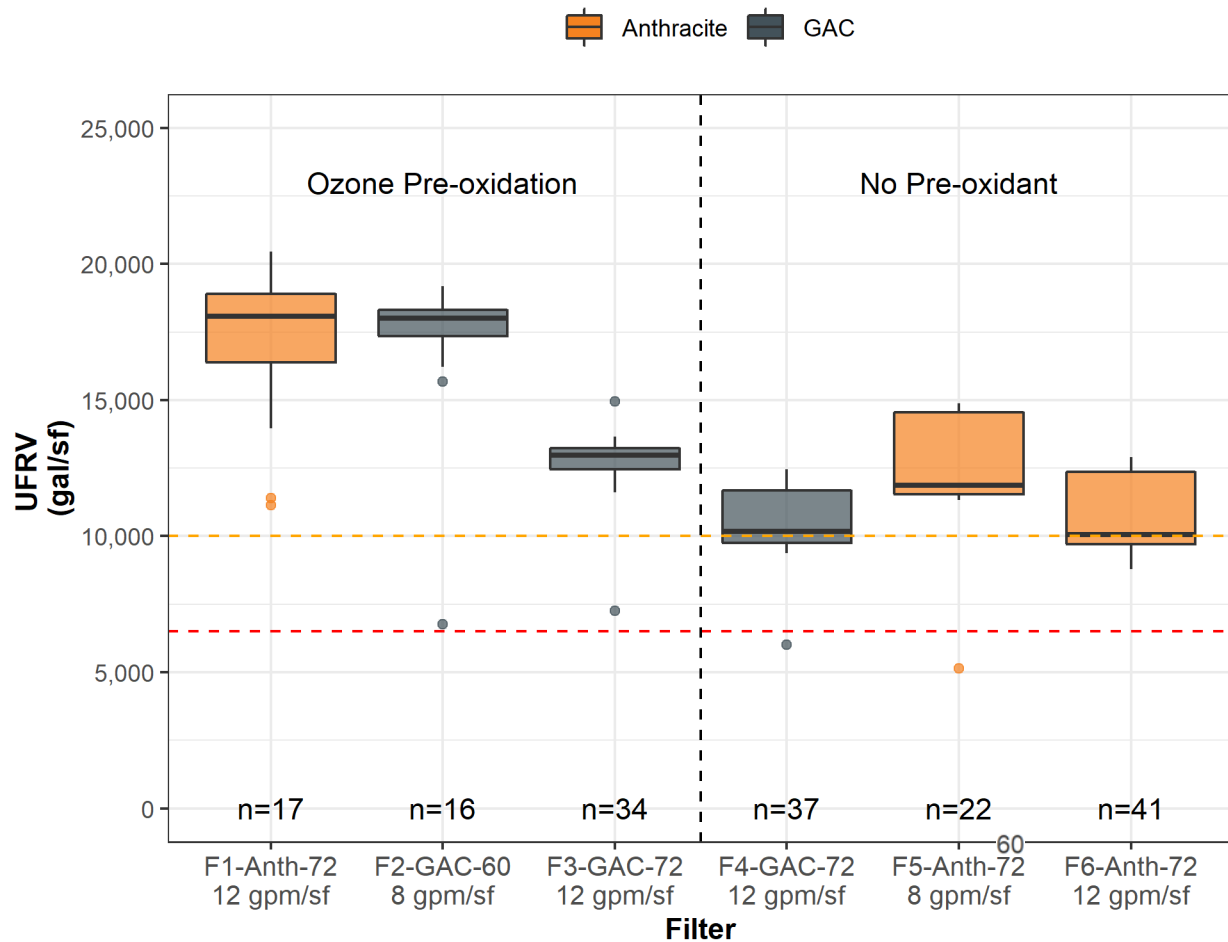


Figure 4-37. Calculated UFRVs during side-by-side testing of pre-oxidation vs. no pre-oxidation, conducted August 30 – September 30

Figure 4-38 shows the filter effluent turbidities recorded during accepted filter runs during this test period. Ozone pre-oxidation appears to have benefited the 72-inch GAC column (Filter 3), whose median filter effluent turbidity was almost half that of the corresponding column filtering water that had not been treated with a pre-oxidant (Filter 4). Interestingly, this trend was not observed for the two 72-inch anthracite columns. Instead, the column filtering water that had not been treated with a pre-oxidant (Filter 6) had a lower median filter effluent turbidity and more consistently lower filter effluent turbidities than the column filtering water that had been treated with ozone as a pre-oxidant (Filter 1).

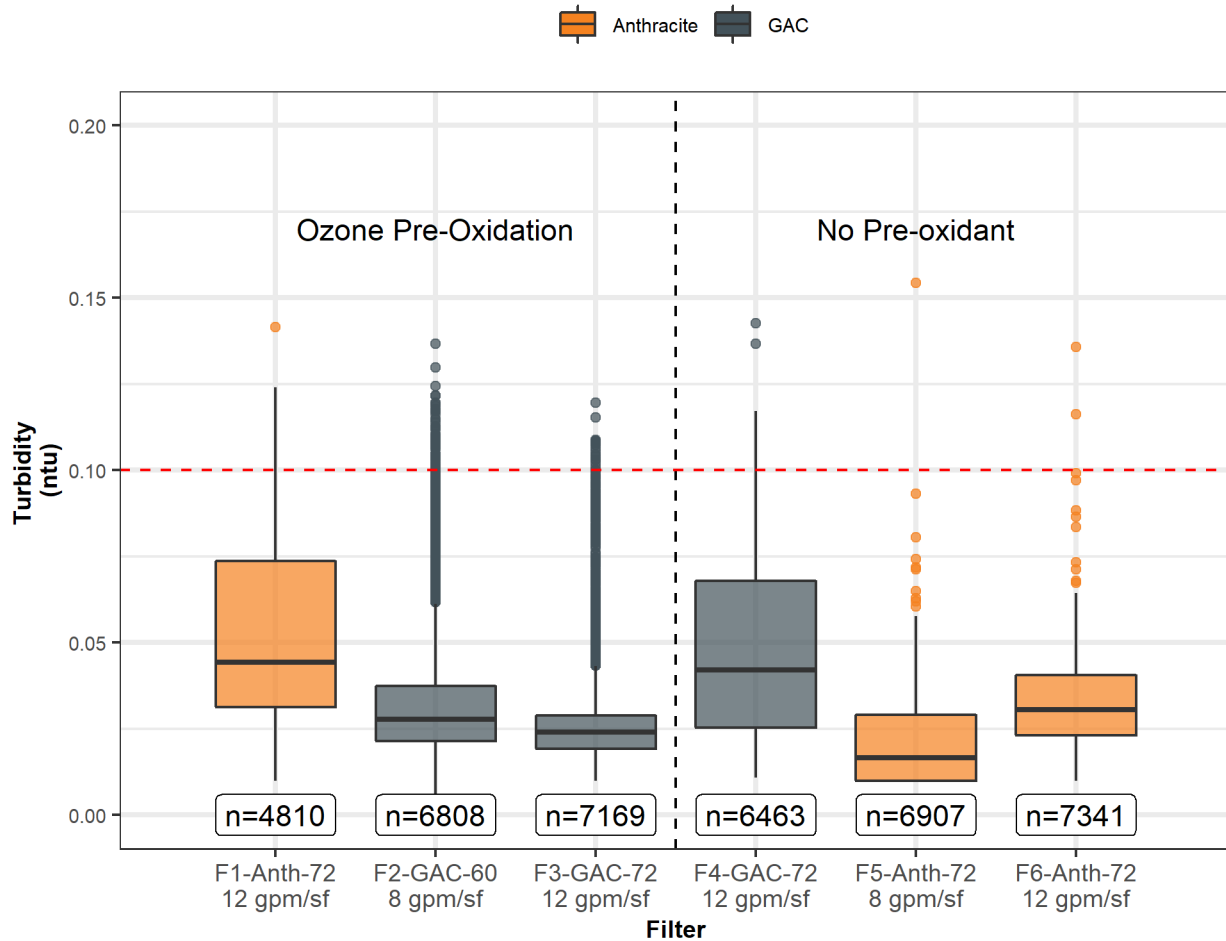


Figure 4-38. Filter effluent turbidities recorded during accepted filter runs during side-by-side testing of pre-oxidation vs. no pre-oxidation, conducted August 30 – September 30

Particle counts from August 30 to September 30 are summarized in Table 4-7. Every filter met the goal of having less than 50 particles/mL in the 5 to 15 μ m range. This filter, which also had the highest filter effluent turbidities during this test period, was just slightly above that goal.

Table 4-7. Raw water and filter effluent particle counts summary, averaged by accepted filter runs during side-by-side testing of pre-oxidation vs. no pre-oxidation, conducted August 30 – September 30

Parameter		Raw Water		Train 1: No pre-oxidation			Train 2: Ozone pre-oxidation		
				F6–Anth–72			F1–Anth–72		
		50th Percentile	95th Percentile	50th Percentile	95th Percentile	Log Removal [†]	50th Percentile	95th Percentile	Log Removal [†]
Turbidity (NTU)		0.52	0.79	0.03	0.04		0.06	0.10	
Particles (counts/mL)	3 to 5 µm	761	870	10	15	1.9	24	28	1.5
	5 to 15 µm	518	612	4	7	2.1	20	26	1.4

Parameter		F5–Anth–60			F2–GAC–60		
		50th Percentile	95th Percentile	Log Removal [†]	50th Percentile	95th Percentile	Log Removal [†]
Turbidity (NTU)			0.02	0.03		0.04	0.06
Particles (counts/mL)	3 to 5 µm		5	9		7	24
	5 to 15 µm		2	6		9	27

Parameter		F4–GAC–72			F3–GAC–72		
		50th Percentile	95th Percentile	Log Removal [†]	50th Percentile	95th Percentile	Log Removal [†]
Turbidity (NTU)			0.05	0.06		0.03	0.04
Particles (counts/mL)	3 to 5 µm		10	18		15	43
	5 to 15 µm		5	11		11	32

[†] Log removals calculated based on the difference between the median raw water and median filter effluent particle counts in the specified size bin.

Review of individual filter runs during this period indicated a shift in particle removal through the filters depending on whether or not the water being filtered had been treated with a pre-oxidant. As illustrated in Figure 4-39, the filter effluent particle counts were strongly influenced by pre-oxidation with ozone. During this period, filters treating water that had been treated with a pre-oxidant were characterized by very low particle counts through the majority of the run, followed by a sharp breakthrough of particles at the end of each run. This potentially could have been mitigated with an adjustment to the filter aid dose used for this train. Filters that received water that had not been treated with a pre-oxidant were found to have higher filter effluent particle counts. While the increase in particle counts in the size ranges of interest (3 – 5 μm and 5 – 15 μm) was moderate, the increase in the smallest size range (2 – 3 μm) was pronounced. However, despite the increase in particle counts from these filters, there was not a marked breakthrough of particles at the end of the filter run. Therefore, the particle count statistics shown in Table 4-7 are somewhat misleading; even though the median and 95th percentiles from the filters receiving water that has not been treated with a pre-oxidant (Filters 4, 5, and 6) are lower than those from the filters treated water that has been pre-oxidized with ozone (Filters 1, 2, and 3), the filter effluent particle counts from the latter filters are lower through the majority of the run. It is only the breakthrough of particles at the end of the runs that inflate the statistics for the filters receiving water treated with a pre-oxidant.

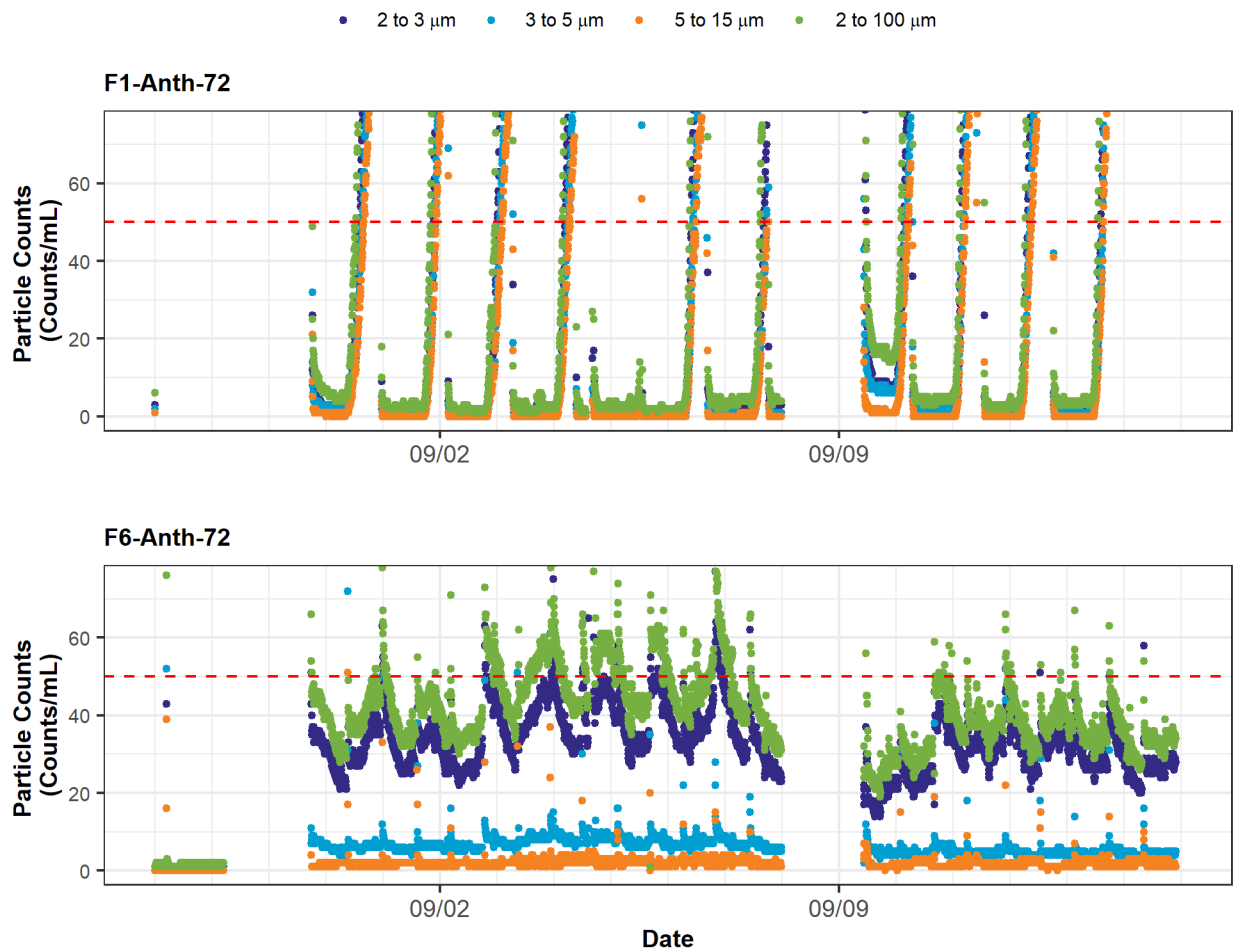


Figure 4-39. Comparison of particle counts from 72-inch anthracite filters treating water that has been pre-oxidized with ozone (Filter 1, top) vs. water that has not been pre-oxidized (Filter 6, bottom)

Organics data were analyzed from the pre-ozonation vs no pre-oxidation trial conducted from August 30 to September 29, for TOC, filtered UV₂₅₄ and true color removal. Pre-treatment was applied with an ozone dose of 0.5 mg/L O₃ to Train 2 (Filters 1, 2, 3) from August 30 to September 16, followed by a period with an increased dose of 1 mg/L O₃. Both trains were fed PACl at a dose of 3.5 mg/L and filter aid at a dose of 0.01 mg/L. Figure 4-40 and Figure 4-41 compare TOC data from the filter effluent from the two groups of filters with the same media, depth, and filtration rate, in order to directly compare the filter performance based on the pre-treatment: the 72-inch anthracite filters at the high filtration rate and the 72-inch GAC filters at the high filtration rate, respectively. Similar figures are presented for the filtered UV₂₅₄ data (Figure 4-42 and Figure 4-43), and true color data (Figure 4-44 and Figure 4-45). Organics data for Filters 2 and 5 are presented in the filter comparison section (Section 5.4) to compare organics removal at different filtration rates.

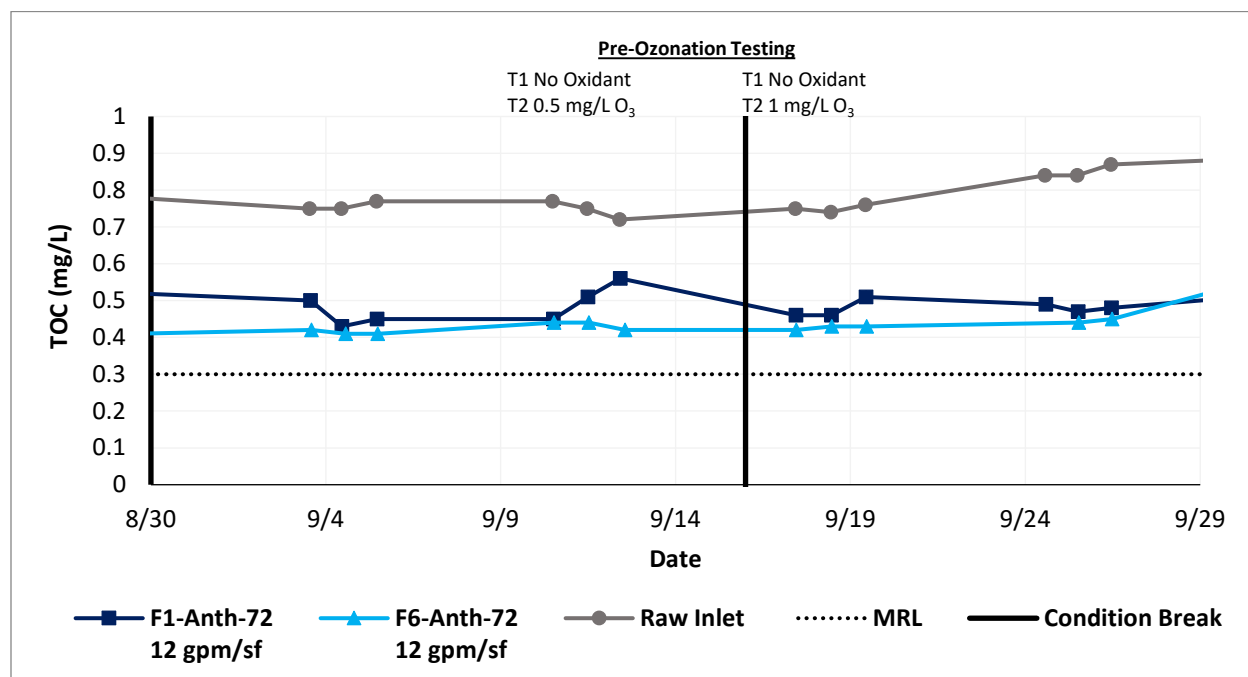


Figure 4-40. Organics Removal for Filters 1 and 6 - pre-ozonation vs no pre-oxidation: TOC

TOC in Filter 1 (Train 2 [T2] - Pre-ozonation) and Filter 6 (Train 1 [T1] – No pre-oxidation) effluent August 30 to September 29.

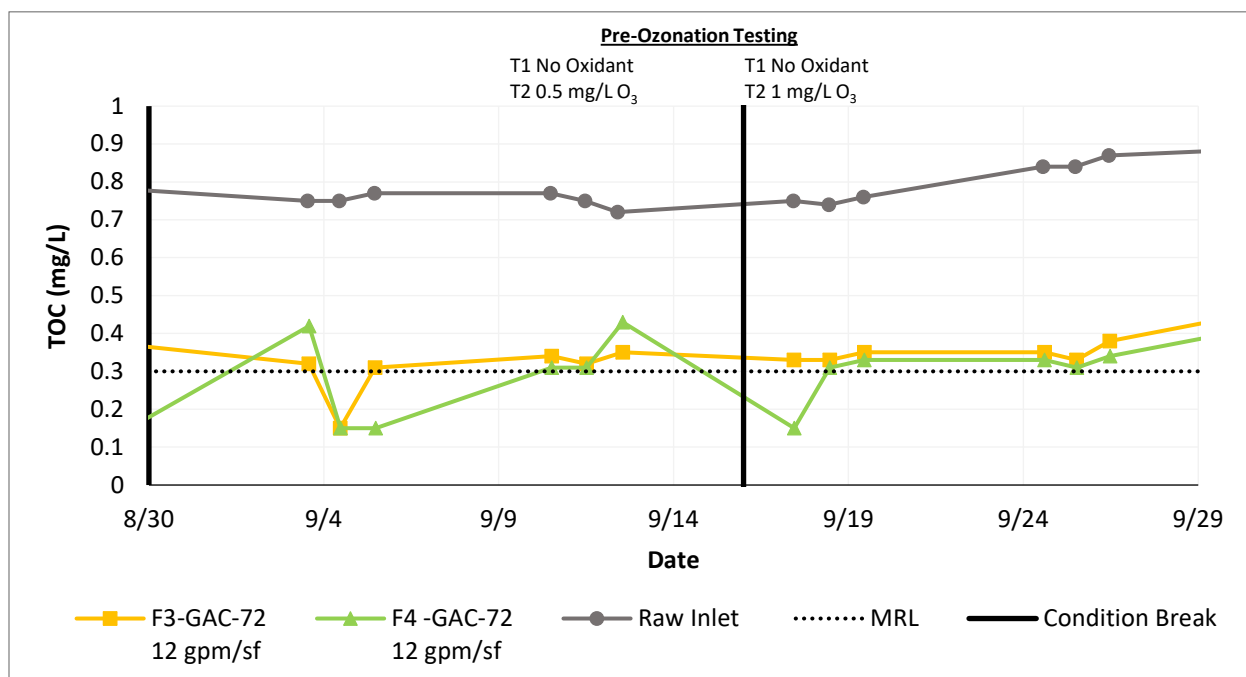


Figure 4-41. Organics Removal for Filters 3 and 4 - pre-ozonation vs no pre-oxidation: TOC

TOC in Filter 3 (Train 2 [T2] - Pre-ozonation) and Filter 4 (Train 1 [T1] - no pre-oxidation) effluent from August 30 to September 29.

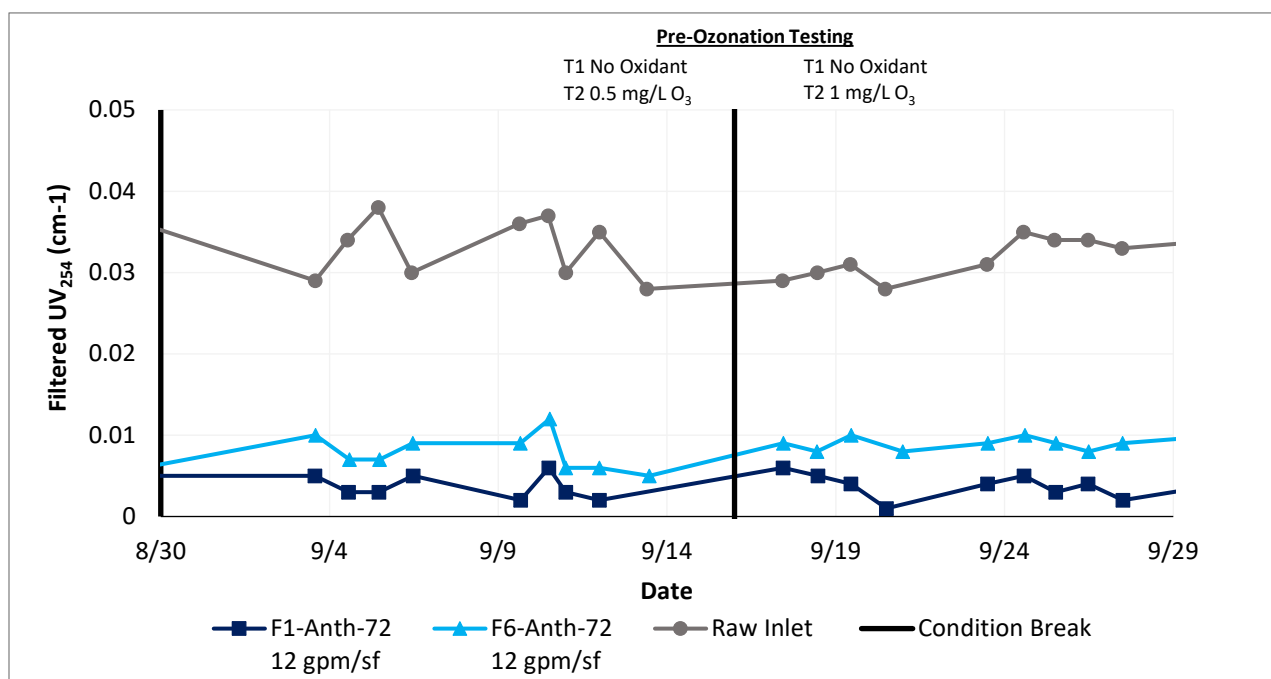


Figure 4-42. Organics Removal for Filters 1 and 6 - pre-ozonation vs no pre-oxidation: filtered UV₂₅₄

Filtered UV₂₅₄ in Filter 1 (Train 2 [T2]– Pre-ozonation) and Filter 6 (Train 1 [T1] – no pre-oxidation) effluent from August 30 to September 29.

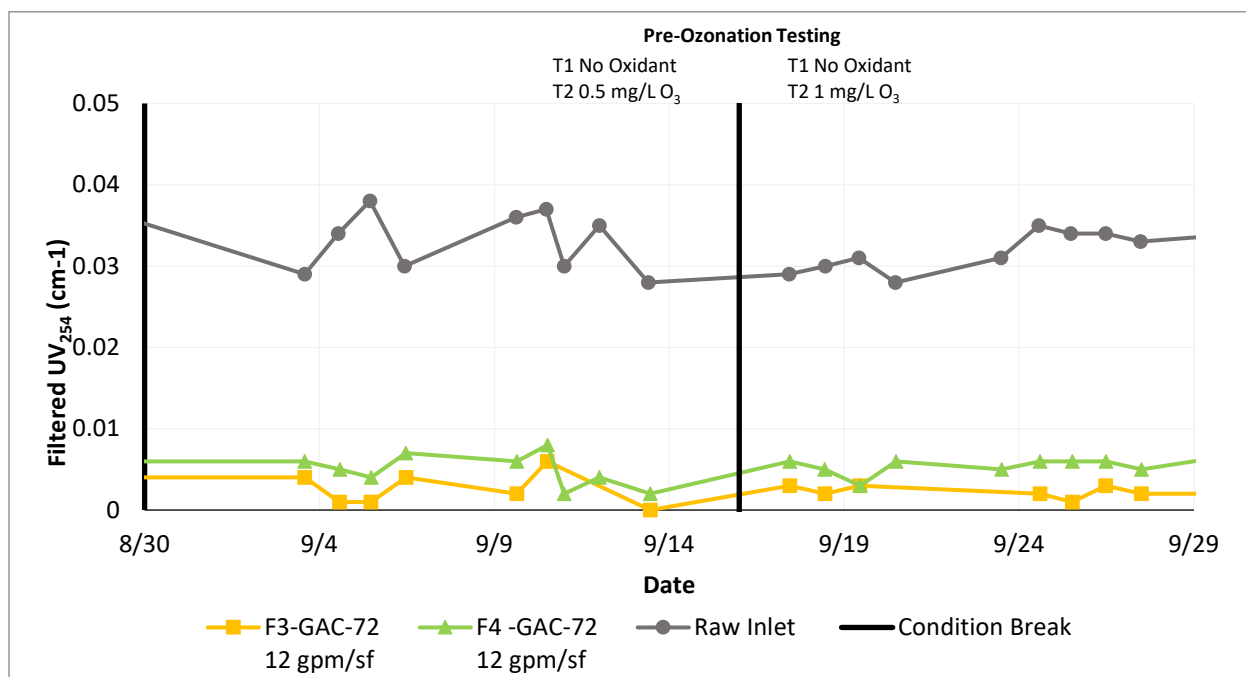


Figure 4-43. Organics Removal for Filters 3 and 4 - pre-ozonation vs no pre-ozonation: filtered UV₂₅₄

Filtered UV₂₅₄ in Filter 3 (Train 2 [T2] – Pre-ozonation) and Filter 4 (Train 1 [T1] – no pre-oxidation) effluent from August 30 to September 29.

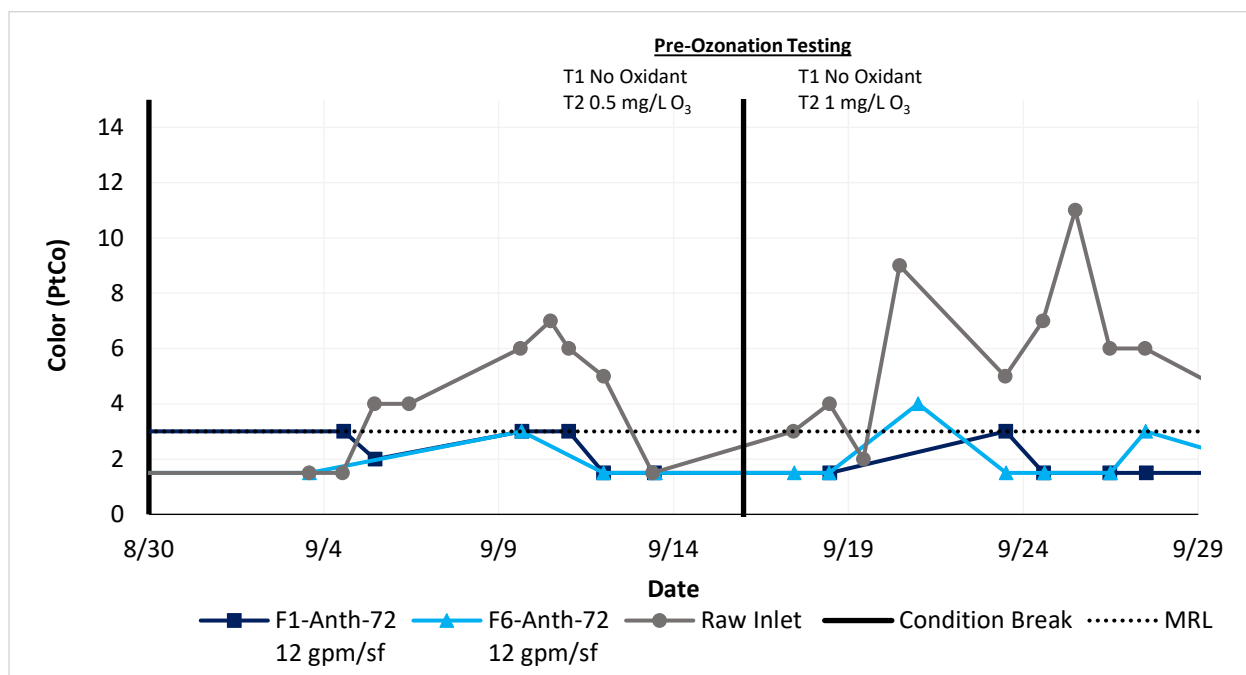


Figure 4-44. Organics Removal for Filters 1 and 6 - pre-ozonation vs no pre-oxidation: true color

True color in Filter 1 (Train 2 [T2] – Pre-ozonation) and Filter 6 (Train 1 [T1] – no pre-oxidation) effluent from August 30 to September 29.

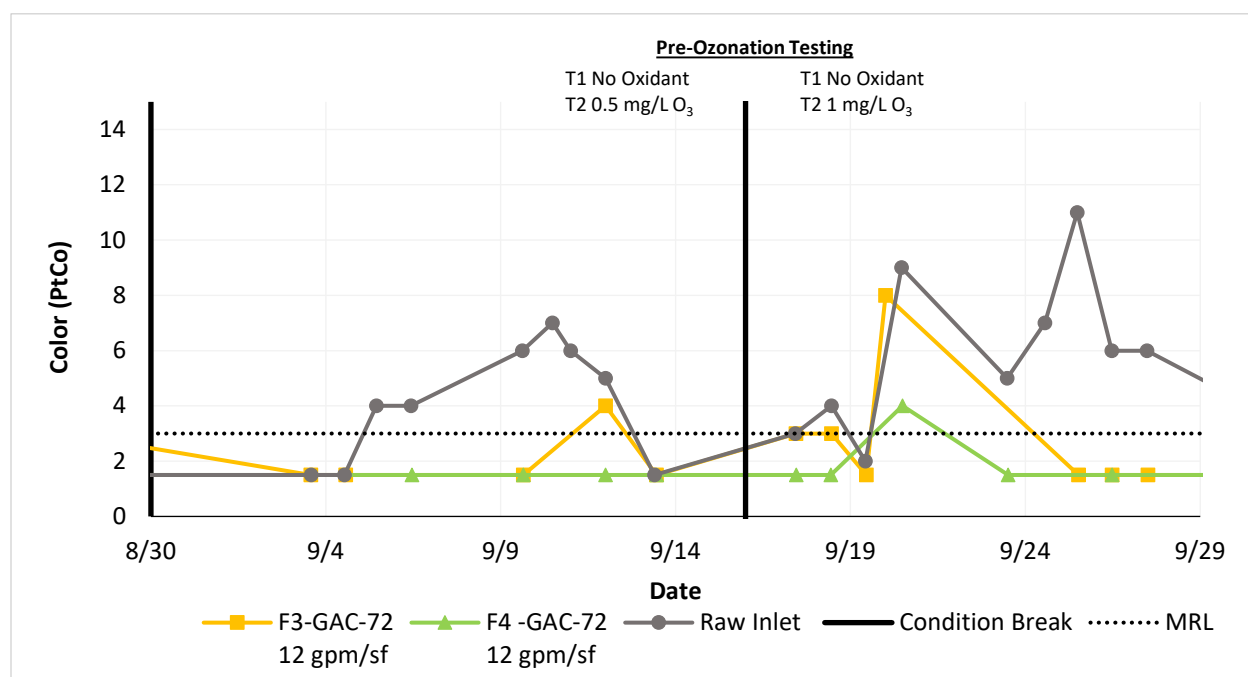


Figure 4-45. Organics Removal for Filters 3 and 4 - pre-ozonation vs no pre-oxidation: true color

True color in Filter 3 (Train 2 [T2] – Pre-ozonation) and Filter 4 (Train 1 [T1] – no pre-oxidation) effluent from August 30 to September 29.

Based on a review of TOC, UV₂₅₄ and color before and after the ozone dose change from 0.5 to 1.0 mg/L O₃, there was no noticeable difference in organics removal related to the ozone dose change, as expected (Figure 4-40 through Figure 4-45). In addition, throughout the period, TOC and color removal were not improved with the addition of pre-ozone, while UV₂₅₄ reduction increased for both filters in Train 2 with the ozone applied.

Table 4-8 provides a summary of the average organics removal from the raw to the filtered effluent to further compare organics removal during the pre-ozonation testing period. In addition, average TOC, filtered UV₂₅₄ data, and true color data by location are presented in Figure 4-46 through Figure 4-48, respectively for the same time period comparing the performance between the trains by location with and without pre-ozonation. During this test scenario, TOC removal was similar between Train 1, which was not pre-oxidized, and Train 2, which was pre-oxidized with ozone (Figure 4-46). TOC is not expected to be removed through ozone directly. This result was observed during the bench-scale ozone testing as well. Filtered UV₂₅₄ in Train 2 on the other hand, as shown in Figure 4-47, was lower, indicating that pre-oxidation is transforming the organics present in the raw water. During this test period, filtered UV₂₅₄ decreased by an average of 92 percent in the ozonated train, compared to 78 percent in the train with no pre-treatment. Color removal was > 50 percent with pre-ozonation and > 63 percent with no pre-oxidation, with removal below the MRL on average for most of the filters (Figure 4-48).

Table 4-8. Average organics removal during pre-ozonation vs. no pre-oxidation testing from August 30 through September 29

Train	Condition	# of samples ^a	TOC (mg/L)	# of samples ^a	Filtered UV ₂₅₄ (cm-1)	# of samples ^a	True Color (Pt-Co)
Influent	None	12	0.78	18	0.03	17	5.0
Train 2 Filter Effluent	Pre-ozonation	36	0.38	44	0.003	32	<3
	% Removal		52%		92%		> 50% ^b
Train 1 Filter Effluent	No pre-oxidation	35	0.38	54	0.007	32	<3
	% Removal		51%		78%		> 63% ^b

a. Combined samples from all three filters in the train for the average and percent removal calculation.

b. The percent removal is represented as > to indicate that the percent removal is based on measurements below the MRL (3 Pt-Co).

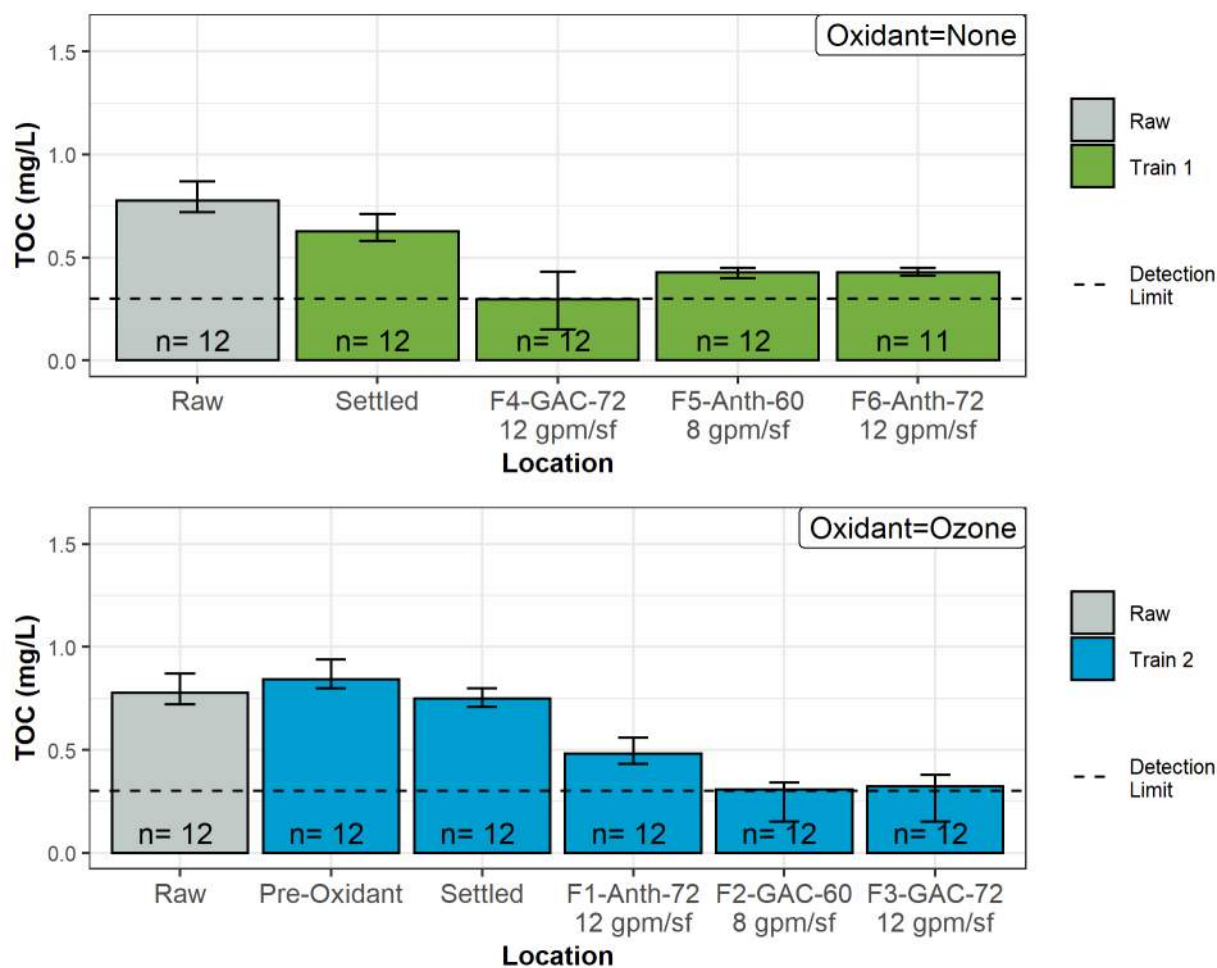


Figure 4-46. Average TOC by location during comparison of pre-ozonation (Train 2) vs. no pre-oxidation (Train 1) from August 30 to September 29

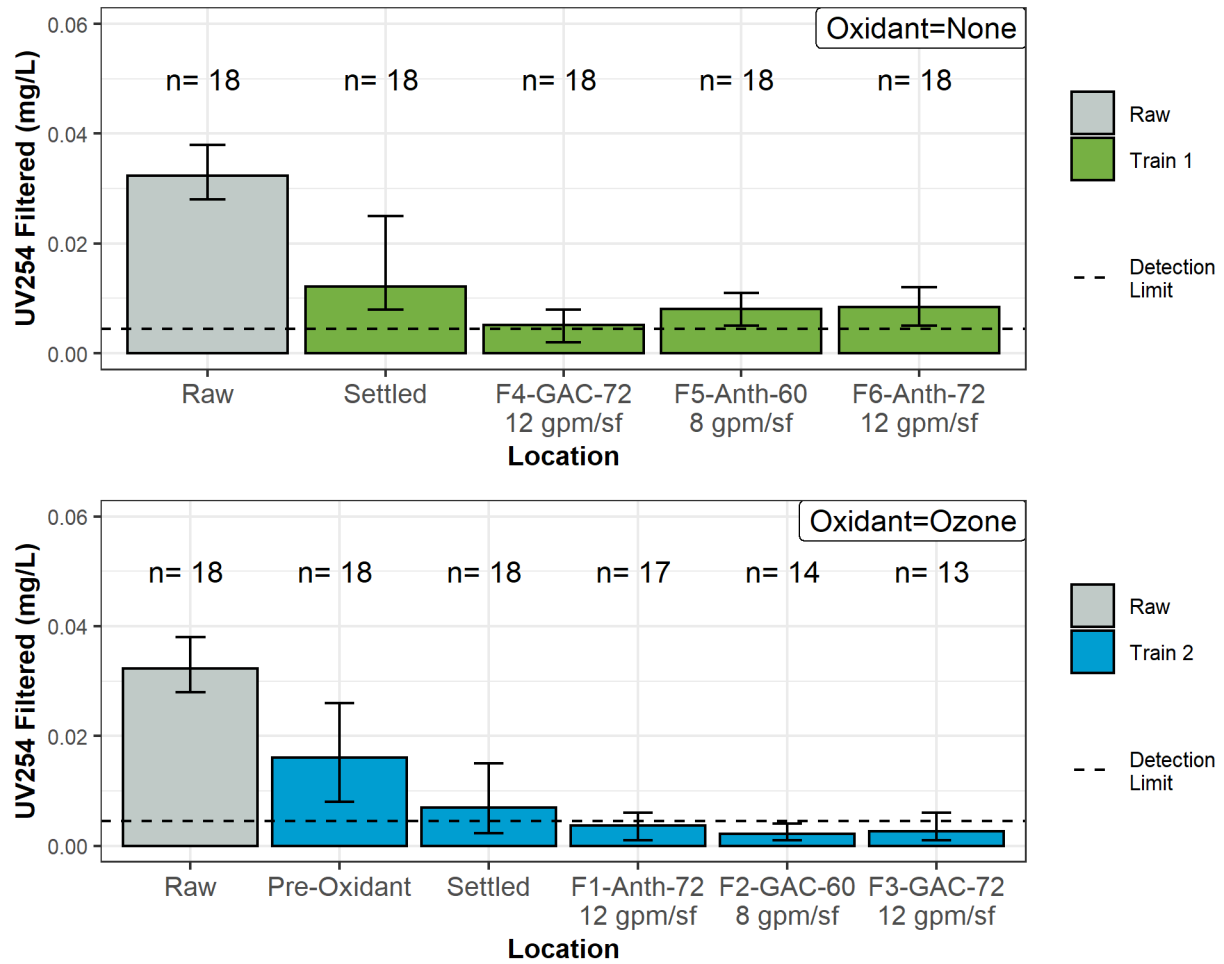


Figure 4-47. Average Filtered UV₂₅₄ by location during comparison of pre-ozonation (Train 2) vs. no pre-oxidation (Train 1) from August 30 to September 29

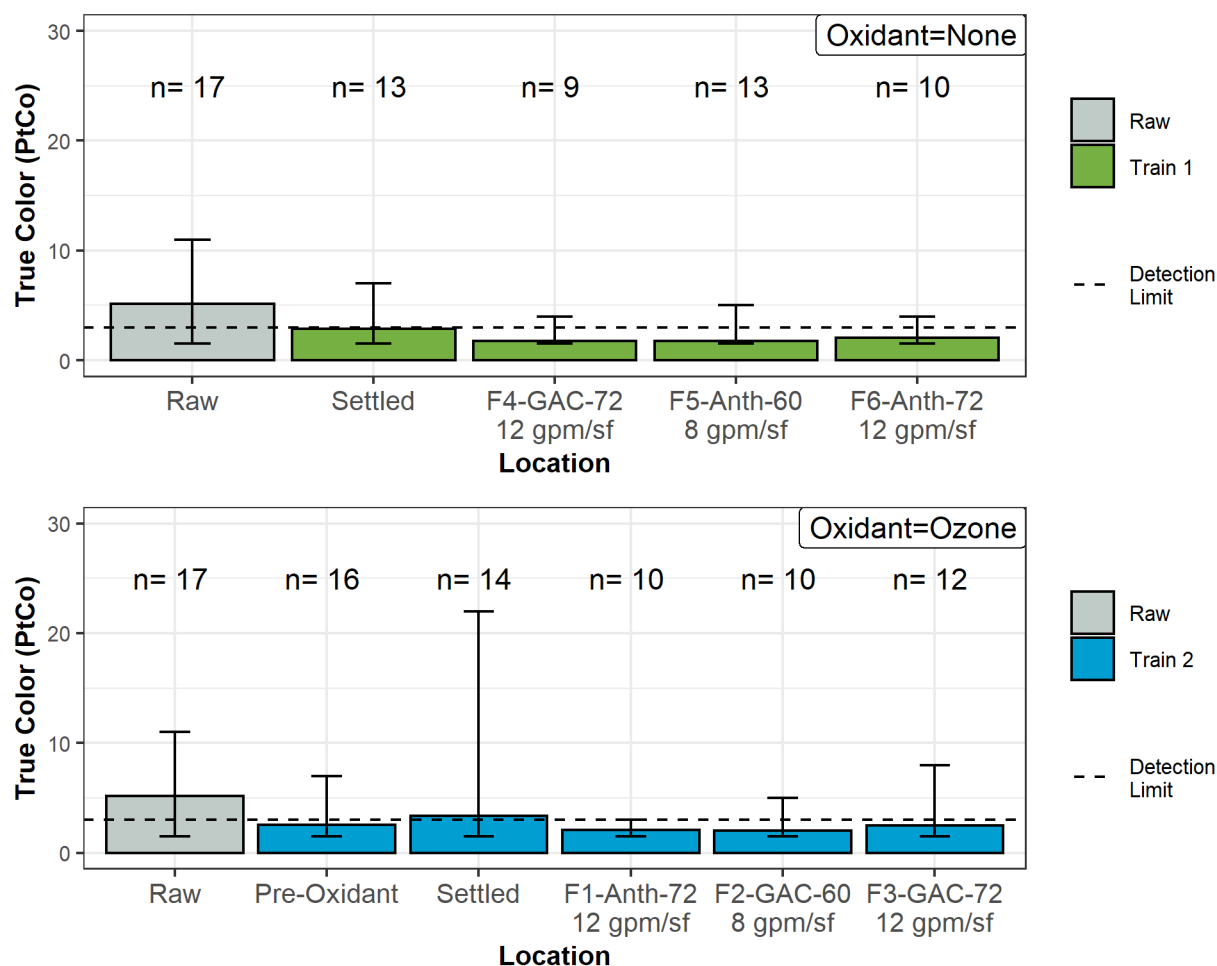


Figure 4-48. Average true color by location during comparison of pre-oxidation (Train 2) vs. no pre-oxidation (Train 1) from August 30 to September 29

4.3.2.1 Summary

This period of testing evaluated how pre-oxidation with ozone influenced pilot plant behavior. Pre-oxidation increased filter productivity, as measured by filter UFRVs. Compared against the train that was not treated with pre-oxidant, pre-oxidation resulted in lower filter effluent turbidities in the GAC filters but higher filter effluent turbidity in the anthracite filters.

The most pronounced treatment difference observed was in filter effluent particle counts. Filtered effluent particle counts from the filters receiving water treated with pre-oxidant were lower than those from the train without pre-oxidant. However, the train that was treated with pre-oxidant also had a sharp particle breakthrough at the end of each filter run, which was not observed in the other train. This particle breakthrough may be attributable to pre-oxidation, or it may be influenced by other treatment parameters such as the filter aid polymer dose applied to both trains. Future testing will evaluate the breakthrough of particles at the end of filter runs to determine the controlling water treatment parameters.

Organics removal between the two trains was largely similar. Pre-oxidation with ozone did result in lower filter effluent UV_{254} values compared to the train without pre-oxidant, while TOC removal was unaffected by pre-oxidation.

4.3.3 Pre-chlorination vs Pre-ozonation

To evaluate performance of different pre-oxidants (chlorine and ozone), a trial was completed comparing pre-chlorine in Train 1 to pre-ozone in Train 2, as shown in Figure 4-49, from October 14 to 21. During this evaluation, both trains were operated in conventional filtration mode. Ozone was dosed at 1.0 mg/L and chlorine was dosed at 0.3 mg/L. These doses were chosen such that all oxidant residual was consumed before being applied to the filters. Both trains were fed PACI at a dose of 3.5 mg/L, until the dose in both trains was slightly reduced to 3.4 mg/L PACI around 5 p.m. on October 18, shortly before the plant was shut down due to a power outage at Headworks. Non-ionic filter aid (Clarifloc N-6310) was injected at the settled water discharge to the filters, where it was fed at a nominal dose of 0.01 mg/L in both trains.

There was a sharp increase in the influent organics levels corresponding to expected seasonal variation and to changing the raw water reservoir intake elevation around the same time as the plant shutdown on October 18. Adjusting to this raw water change limited confidence in some of the UFRV and particle count data for a time. Data presented for this test period were limited to October 14 to 18 as a result. The pre-chlorine vs pre-ozone data set will become more robust as testing continues into November, including effects of different doses.

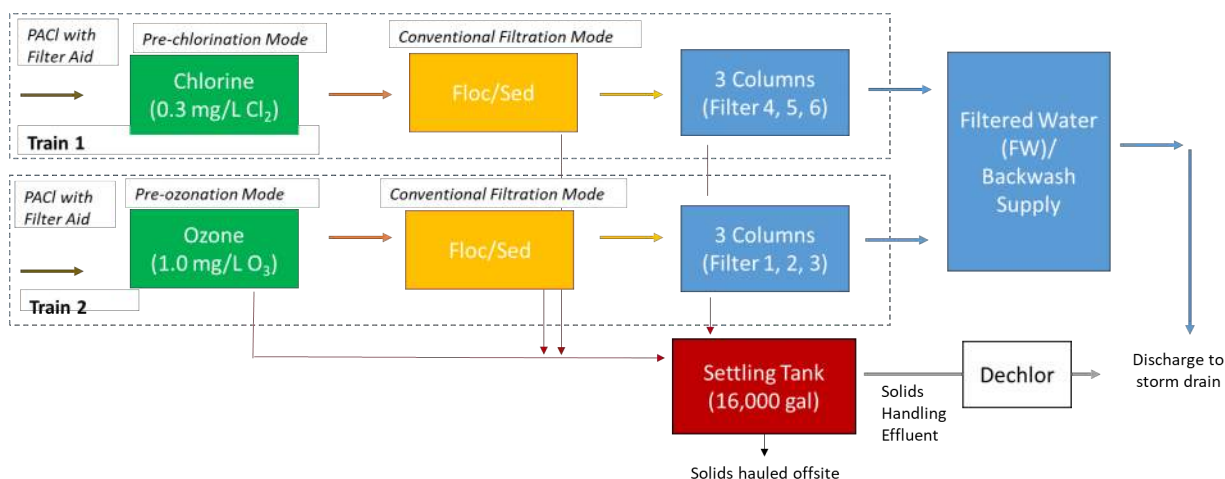


Figure 4-49. Treatment train for pre-chlorination vs. pre-ozonation

A comparison of UFRV value differences for pre-chlorination vs. pre-ozone during this test period is illustrated in Figure 4-50. Examination of Figure 4-50 indicates very little significant differences in UFRV performance between the two pre-oxidants at the dosage ranges used. Additionally, there appears to be less statistical variations for the pre-chlorination scenario as opposed to pre-ozone, suggestive of potentially more stable operations with pre-chlorination. All of the filters exceeded the water quality goal for a UFRV in excess of 6,500 gal/sf-run, 95 percent of the time. In almost all cases, the median value of the UFRVs exceed 10,000 gal/sf-run (except for the pre-chlorinated GAC filter operating at 12 gpm/sf). It should be noted that only a small chlorine dose of 0.3 mg/L is used in comparison to the 1.0 mg/L ozone dose, and it is unknown if a higher pre-chlorine dose (somewhat comparable to the ozone dose used) would have shown more equivalent or perhaps better UFRV performance than pre-ozone. The conservative observation from this limited testing suggests very similar UFRV performance of these two pre-oxidants tested can be expected over the dose ranges indicated. Further testing during additional seasons is planned to validate the results obtained during this week of testing, and to evaluate the impact of higher chlorine pre-oxidant dosages.

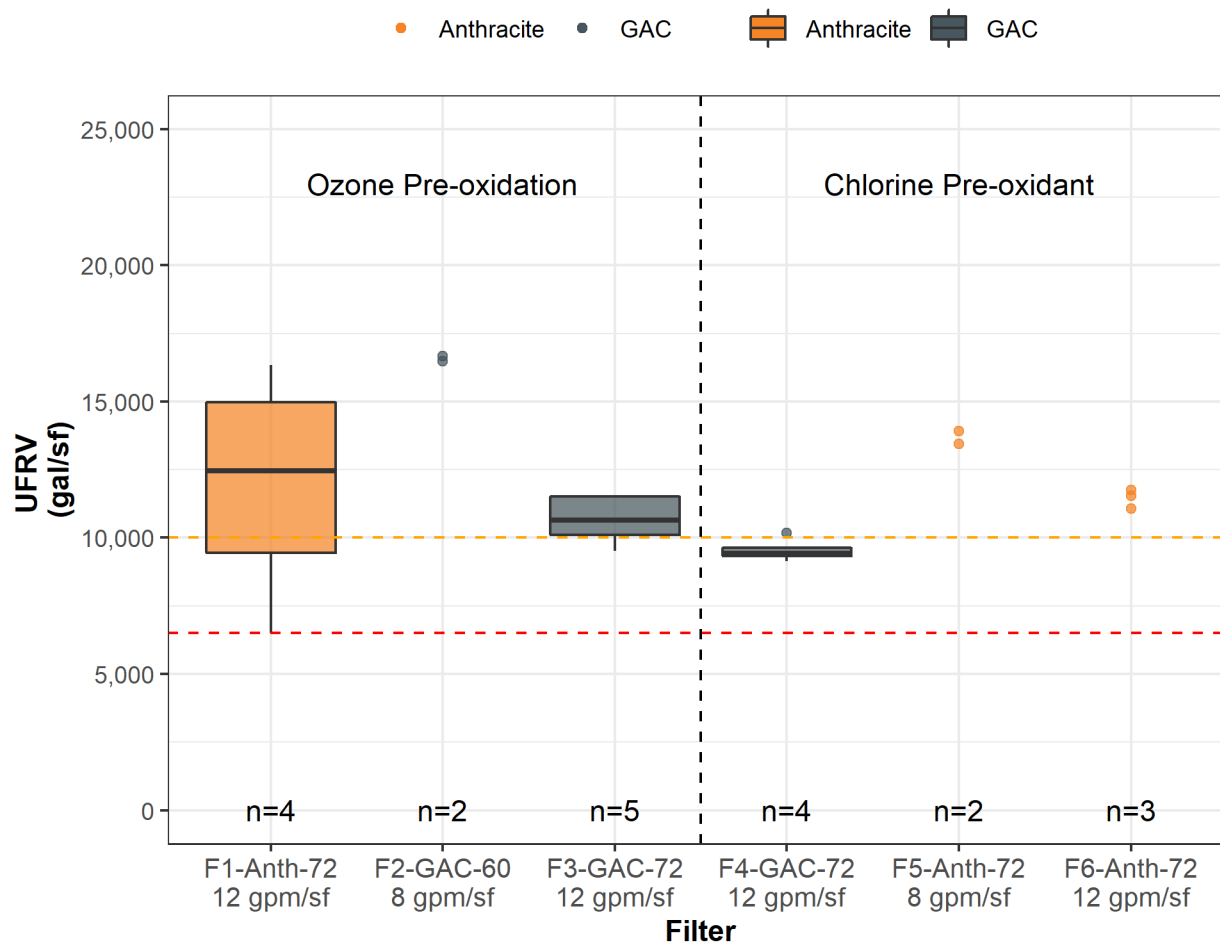


Figure 4-50. Calculated UFRVs during side-by-side testing of ozone vs. chlorine pre-oxidation, conducted October 14 – 18

Filter effluent turbidities corresponding to the accepted filter runs during this test period are shown in Figure 4-51. In general, filter turbidities were quite low, with all filters except Filter 3 consistently remaining below 0.05 NTU.

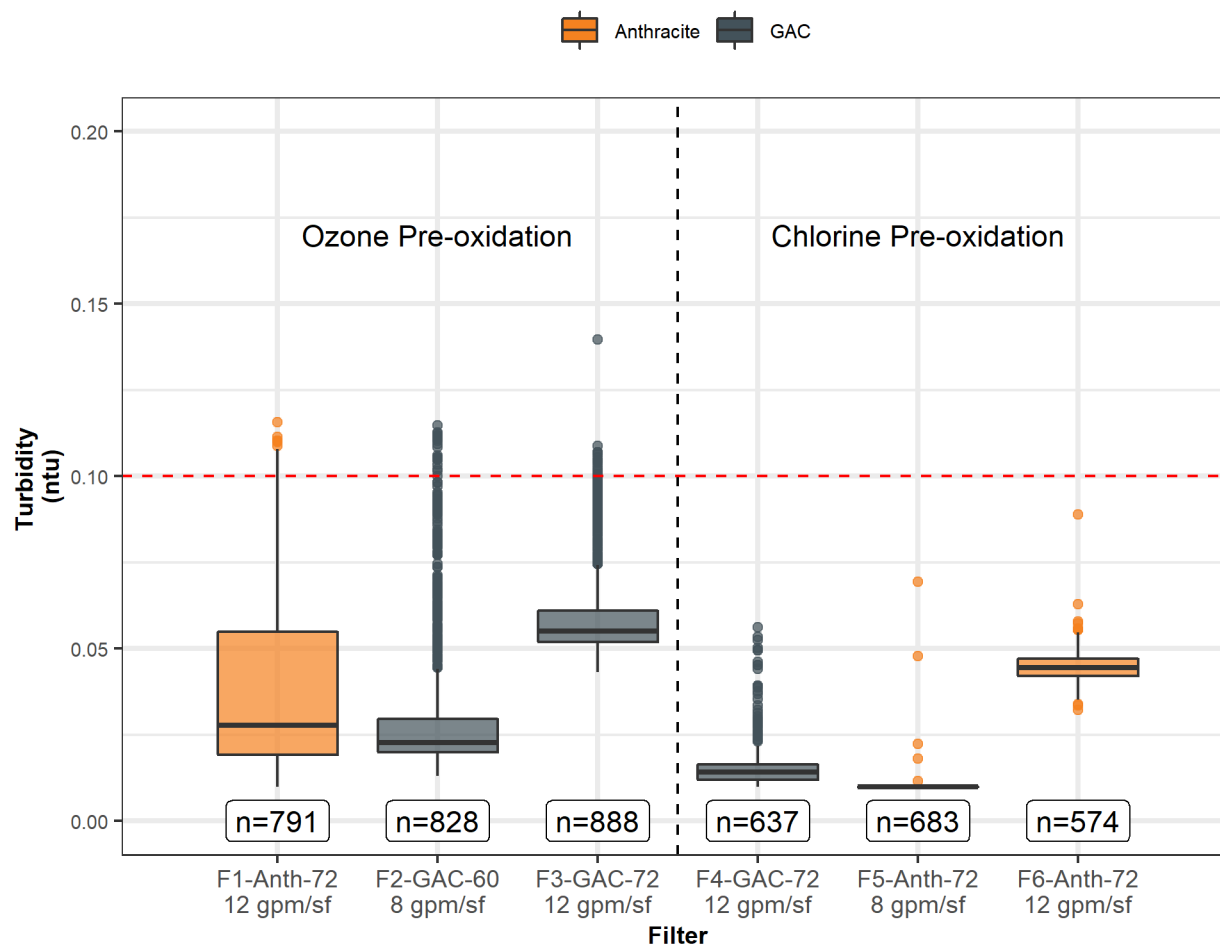


Figure 4-51. Filter effluent turbidities recorded during accepted filter runs during side-by-side testing of ozone vs. chlorine pre-oxidation, conducted October 14 – 18

The comparison of filtered water particle counts for these two pre-oxidants is shown in Table 4-9. Here, a trend is noted that particle counts with pre-chlorination tend to be lower than particle counts with pre-ozonation. Additionally, particle counts the effluent of two of the three filters on the pre-chlorination train (Filters 4 and 5) maintain filter effluent particle counts in the relevant size ranges below the 50 count/mL threshold more than 95 percent of the time. None of the filters in the train using ozone as a pre-oxidant were able to meet this criterion. As with the previous test period the higher particle counts appear to be associated with breakthrough at the end of filter runs. When looking at individual filter runs, filter effluent particles are generally in single-digits through the majority of the run.

This test period did coincide with an increase in raw water particle counts, which allowed for a better understanding of the extent of particle removal through the filters. During this period Filters 5 and 6 averaged greater than 2-log removal in the both the 3 – 5 μm and 5 – 15 μm size ranges. The other filters averaged between 1.5- to 1.9-log removal during the same period. However, it should be noted that raw water particle counts were still relatively low throughout this test period. The 95th percentiles in the 3 – 5 μm and 5 – 15 μm size ranges were 716 and 610 counts/mL, respectively. Demonstrating 2-log particle removal still requires single-digit filter effluent particle counts when raw water particle counts are this low.

Table 4-9. Raw water and filter effluent particle counts summary, averaged by accepted filter runs during side-by-side testing of ozone vs. chlorine pre-oxidation, conducted October 14 – 18

Parameter		Raw Water		Train 1: Chlorine pre-oxidation			Train 2: Ozone pre-oxidation		
				F6–Anth–72			F1–Anth–72		
		50th Percentile	95th Percentile	50th Percentile	95th Percentile	Log Removal [†]	50th Percentile	95th Percentile	Log Removal [†]
Turbidity (NTU)		0.58	0.63	0.05	0.07		0.05	0.09	
Particles (counts/mL)	3 to 5 µm	709	716	20	53	1.5	43	120	1.2
	5 to 15 µm	602	610	16	41	1.6	28	76	1.3

Parameter		F5–Anth–60			F2–GAC–60		
		50th Percentile	95th Percentile	Log Removal [†]	50th Percentile	95th Percentile	Log Removal [†]
Turbidity (NTU)			0.02	0.04		0.05	0.09
Particles (counts/mL)	3 to 5 µm		35	38		26	66
	5 to 15 µm		21	23		31	85

Parameter		F4–GAC–72			F3–GAC–72		
		50th Percentile	95th Percentile	Log Removal [†]	50th Percentile	95th Percentile	Log Removal [†]
Turbidity (NTU)			0.02	0.04		0.06	0.09
Particles (counts/mL)	3 to 5 µm		9	46		26	121
	5 to 15 µm		11	44		19	91

[†] Log removals calculated based on the difference between the median raw water and median filter effluent particle counts in the specified size bin.

Figure 4-52 and Figure 4-53 compare TOC data from the filter effluent from the two groups of filters with the same media, depth, and filtration rate in order to directly compare the filter performance based on the pre-treatment: the 72-inch anthracite filters at the high filtration rate and the 72-inch GAC filters at the high filtration rate, respectively. Data observed starting October 22 when there were increased organics in the influent show there was good removal of organics despite filter UFRV and particle count performance still adjusting to the change.

Similar figures are presented for filtered UV₂₅₄ data (Figure 4-54 and Figure 4-55), and true color data (Figure 4-56 and Figure 4-57). Filtering UV₂₅₄ and true color samples through a 0.45 µm filter was discontinued after October 9 when data showed that media filtration through the GAC or anthracite eliminated the need for membrane filtration. Therefore there were no membrane filtered UV₂₅₄ or true color data for the filtered effluent during this testing period and the UV₂₅₄ and apparent color data is considered to be equivalent to the filtered UV₂₅₄ and true color, given that the filtered effluent has been filtered in the pilot prior to sampling.

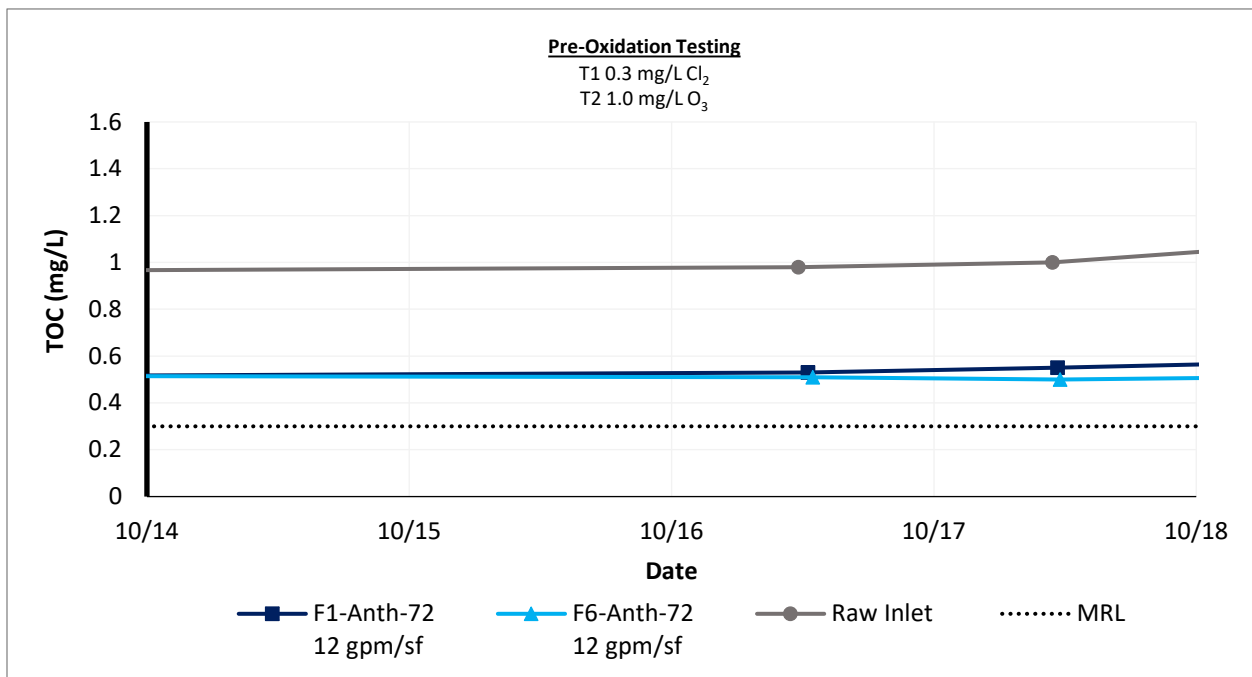


Figure 4-52. Organics Removal for Filters 1 and 6 - pre-chlorination vs no pre-ozonation: TOC

Filter 1 (Train 2 [T2] - Pre-ozonation) and Filter 6 (Train 1 [T1] - Pre-chlorination) effluent from October 14 -18.

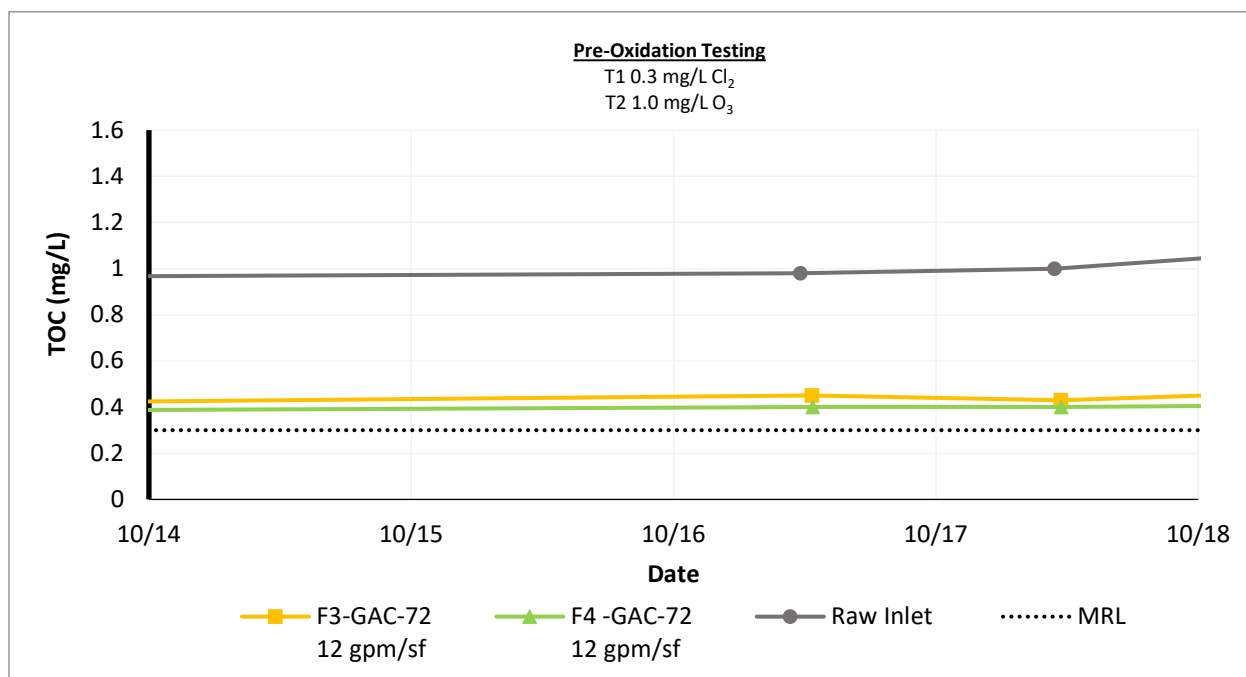


Figure 4-53. Organics Removal for Filters 3 and 4 - pre-chlorination vs no pre-ozonation: TOC

Filter 3 (Train 2 [T2]- Pre-ozonation) and Filter 4 (Train 1 [T1] – Pre-chlorination) effluent from October 14 -18.

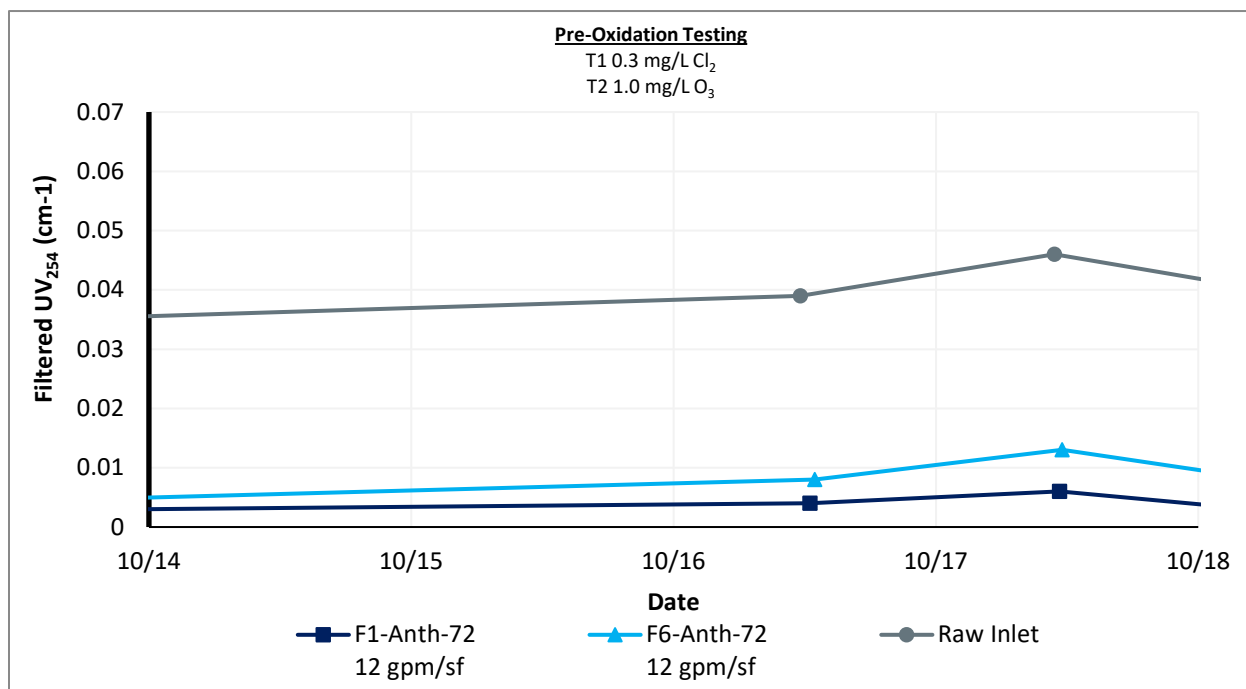


Figure 4-54. Organics Removal for Filters 1 and 6 - pre-chlorination vs no pre-ozonation: Filtered UV₂₅₄

Filter 1 (Train 2 [T2]- Pre-ozonation) and Filter 6 (Train 1 [T1]– Pre-chlorination) effluent from October 14 -18.

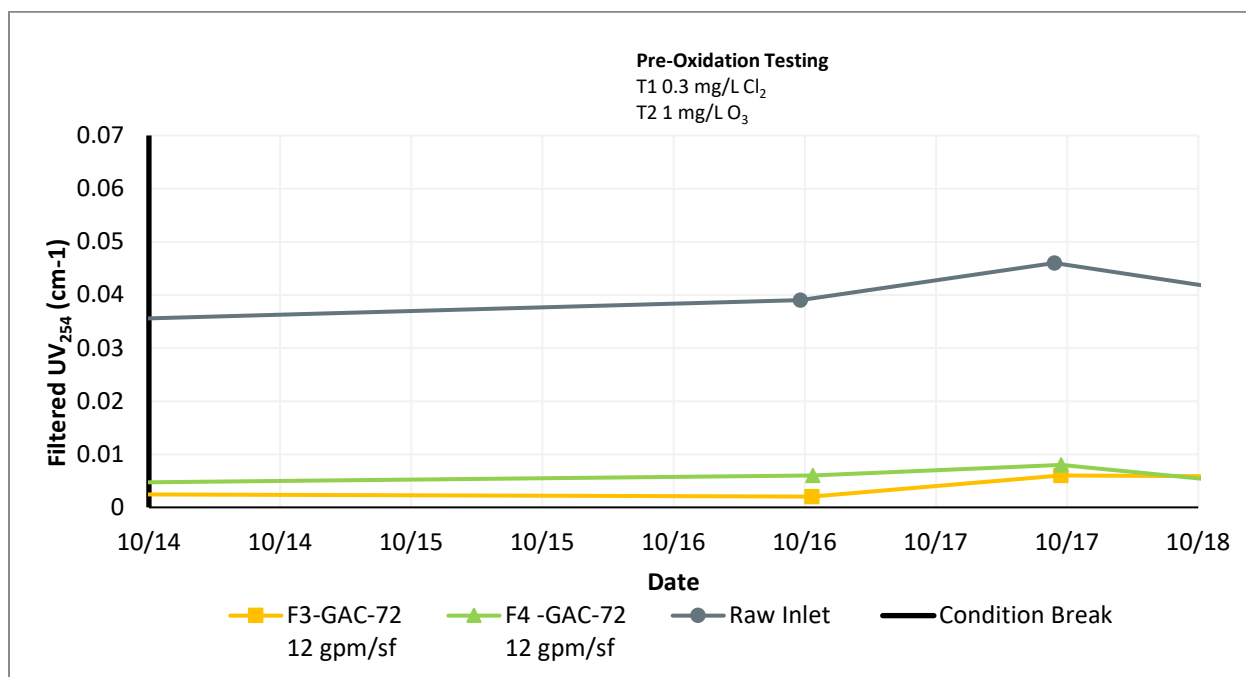


Figure 4-55. Organics Removal for Filters 3 and 4 - pre-chlorination vs no pre-ozonation: Filtered UV₂₅₄
Filter 3 (Train 2 [T2] - Pre-ozonation) and Filter 4 (Train 1 [T1] - Pre-chlorination) effluent from October 14 -18.

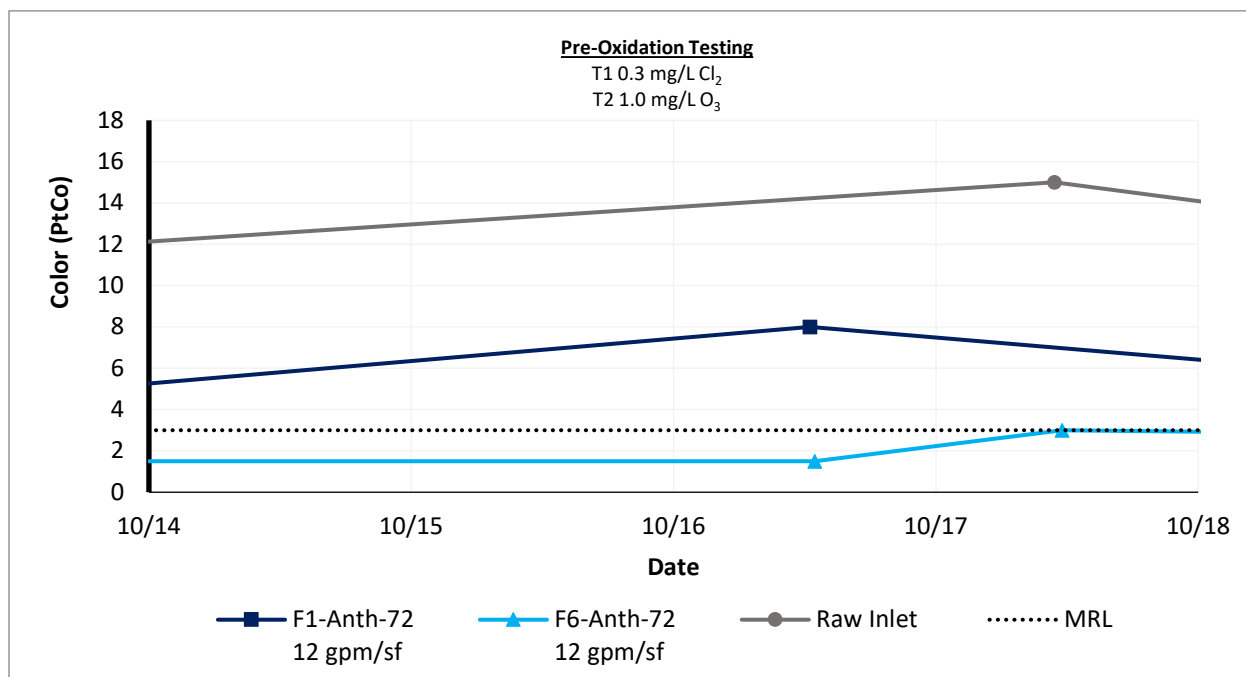


Figure 4-56. Organics Removal for Filters 1 and 6 - pre-chlorination vs no pre-ozonation: True color
Filter 1 (Train 2 [T2] - Pre-ozonation) and Filter 6 (Train 1 [T1] - Pre-chlorination) effluent from October 14 -18. Apparent color data is presented for this period in the absence of true color data.

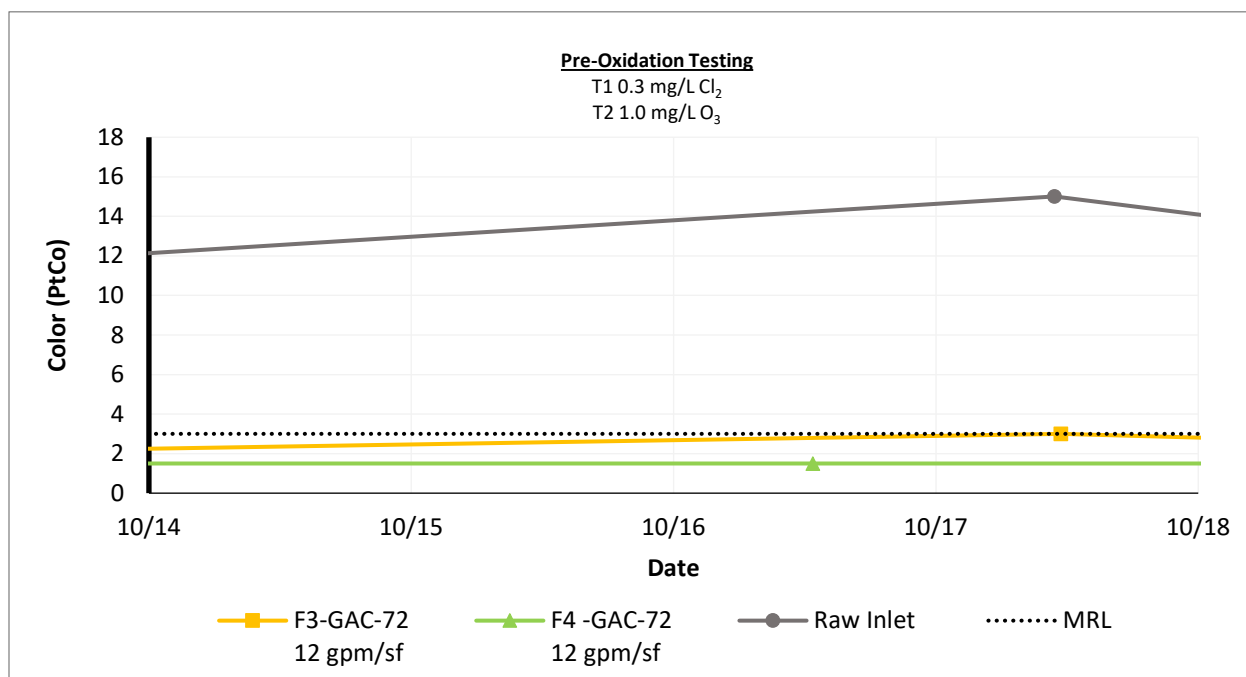


Figure 4-57. Organics Removal for Filters 3 and 4 - pre-chlorination vs no pre-ozonation: True Color

Filter 3 (Train 2 [T2]- Pre-ozonation) and Filter 4 (Train 1 [T1] – Pre-chlorination) effluent from October 14 -18. Apparent color data is presented for this period in the absence of true color data.

Table 4-10 provides a summary of the average organics removal during the pre-chlorination vs. pre-ozonation testing period. Locational data for TOC, filtered UV₂₅₄, and apparent color are presented in Figure 4-58 through Figure 4-60, respectively. UV₂₅₄ in the pre-chlorinated effluent was slightly greater than the pre-ozonated filtered effluent with a percent decrease of 82 percent for the pre-chlorinated train compared to 90 percent when applying ozone. Additionally, both trains showed high levels of color removal.

Table 4-10. Average Organics Removal during pre-chlorination vs. pre-ozonation testing from October 14–October 18

Train	Condition	# of samples ^a	TOC (mg/L)	# of samples ^a	Filtered UV ₂₅₄ (cm ⁻¹) ^b	# of samples ^a	Color (Pt-Co) ^c
Influent	None	2	0.99	2	0.04	1	15
Train 2 Filter Effluent	Pre-ozonation	6	0.47	6	0.004	4	4
	% Removal		53%		90%		72%
Train 1 Filter Effluent	Pre-chlorination	6	0.49	6	0.007	5	<3
	% Removal		51%		82%		>80% ^d

- a. Combined samples from all three filters in the train for the average and percent removal calculation.
- b. Filtered UV₂₅₄ measurements were discontinued for filter effluent after October 9 due to continued contamination from the sample filter. Unfiltered UV₂₅₄ data for filtered effluent were used in the absence of filtered sample data.
- c. True color data were not measured for filtered effluent from October 9 through October 31. Apparent color is presented for that time period in the absence of true color data. Color data that were below the detection limit (3 Pt-Co) were replaced with half the detection limit (1.5 Pt-Co).
- d. The percent removal is represented as ">" to indicate that the percent removal is based on measurements below the MRL (3 Pt-Co).

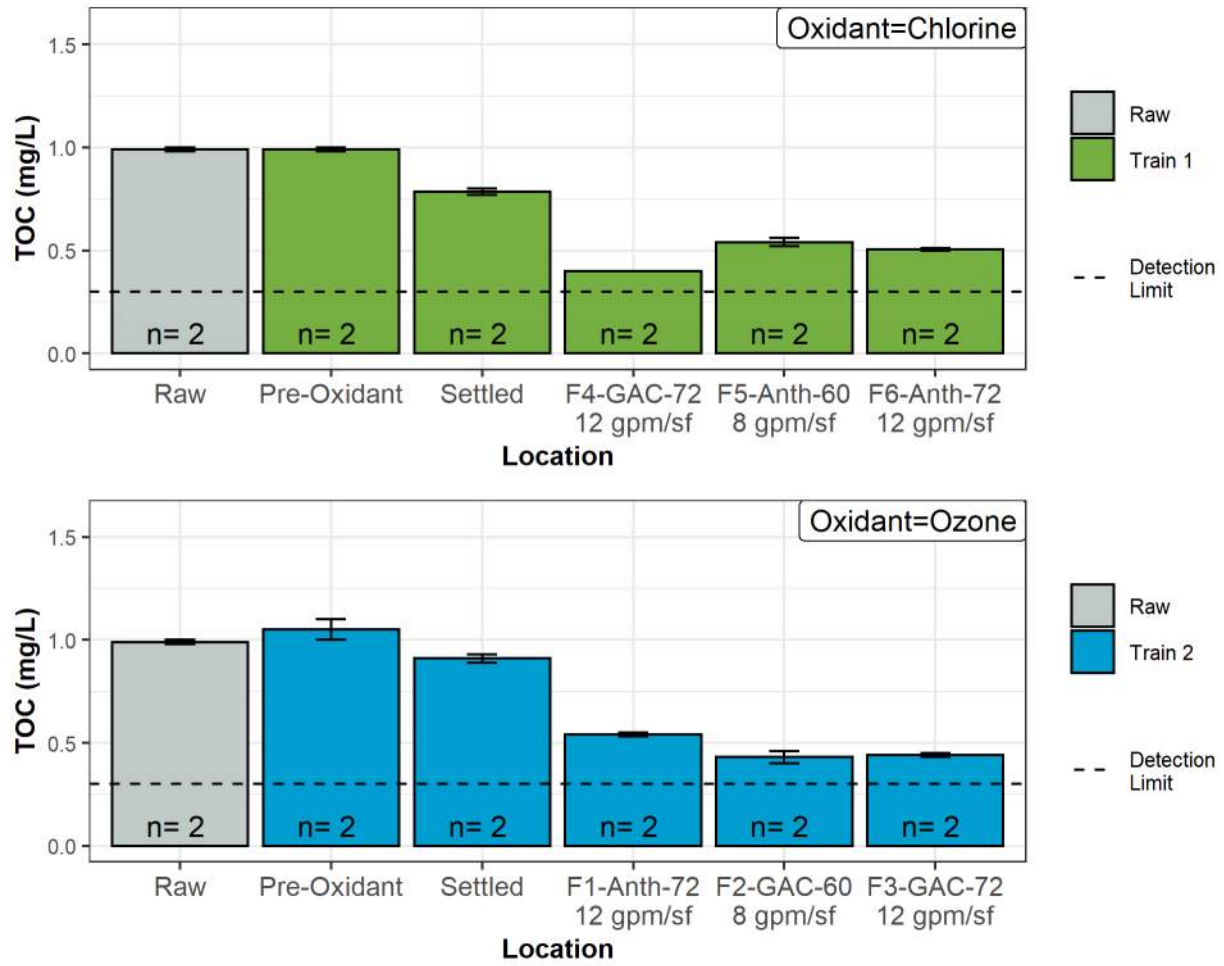


Figure 4-58. Average TOC by location during comparison of pre-chlorination (Train 1) vs pre-ozonation (Train 2) from October 14 - 18

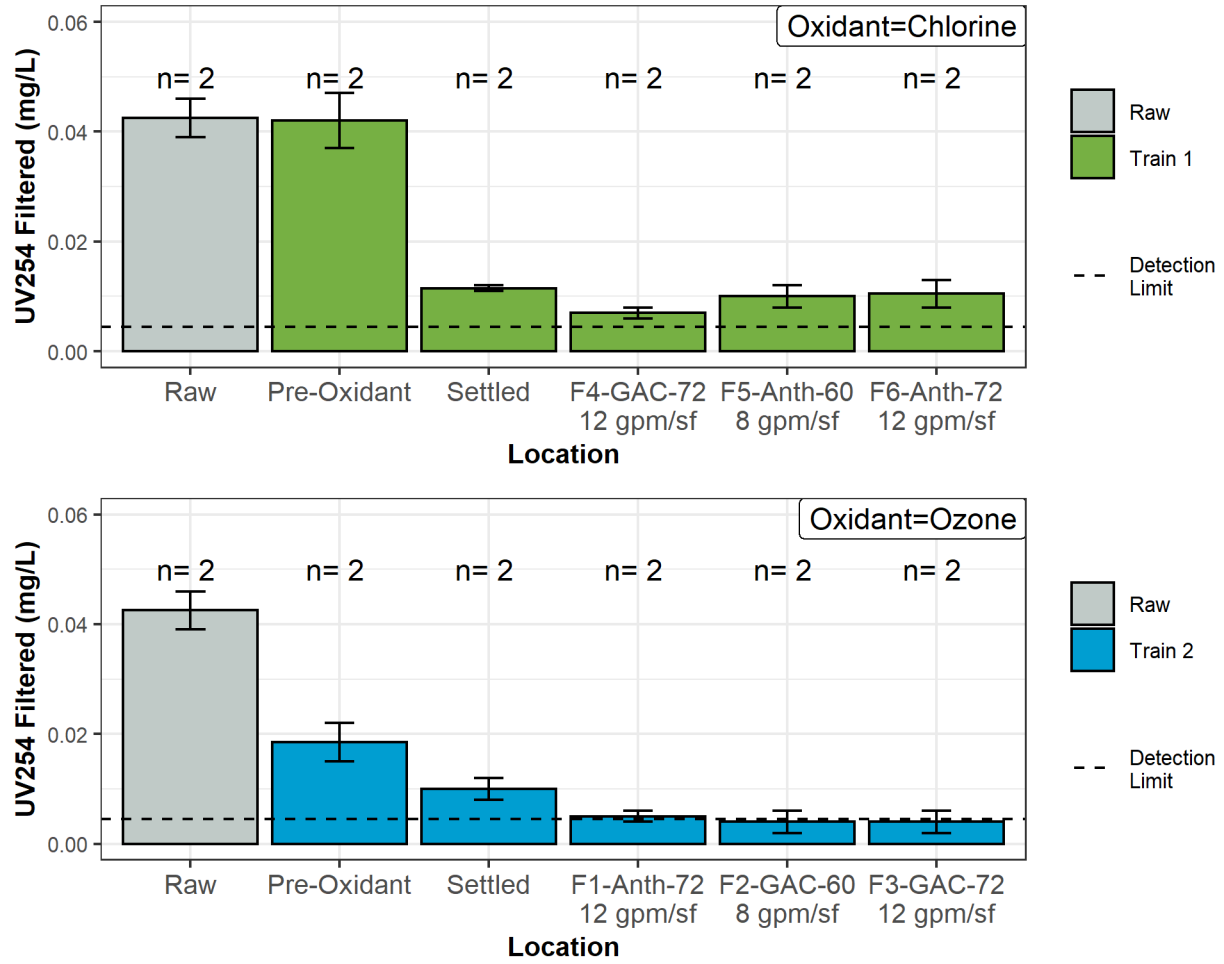


Figure 4-59. Average Filtered UV₂₅₄ by location during comparison of pre-ozonation (Train 2) vs. pre-chlorination (Train 1) from October 14 - 18

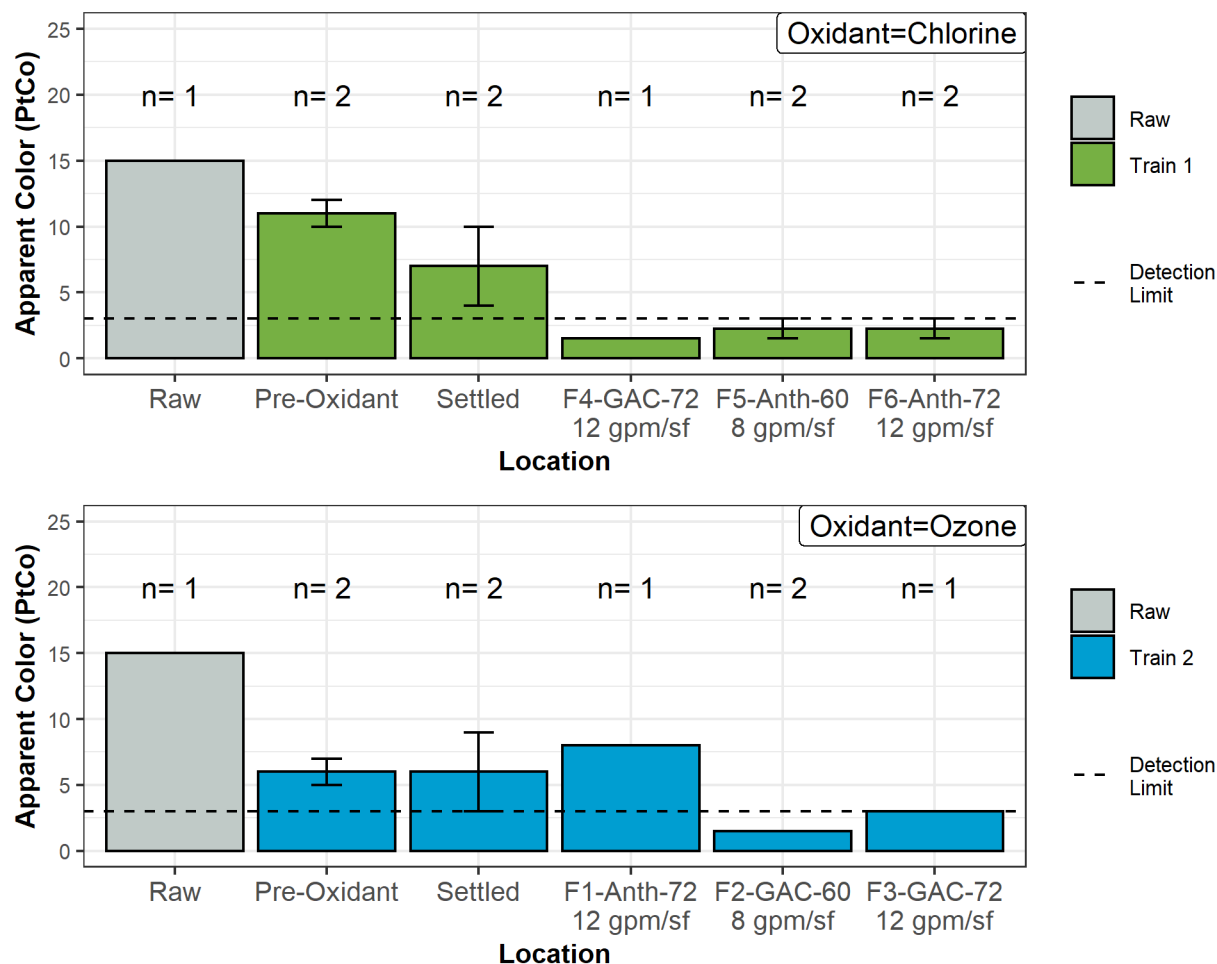


Figure 4-60. Average Color by location during comparison of pre-chlorination (Train 1) vs. pre-ozonation (Train 2) from October 14 - 18.

Apparent color data is presented for this period in the absence of true color data.

4.3.3.1 Summary

This test period compared ozone vs. chlorine when applied as a pre-oxidant. In general, performance between the two trains was similar. There were not large differences between filter productivity, and filter effluent turbidities from all filters were generally low (≤ 0.05 NTU). Particle counts in the filter effluent from the train with pre-chlorination were slightly lower than those from the train with pre-ozonation. As with the previous trial, the higher filter effluent counts were attributable to particles associated with breakthrough at the end of filter runs; particle counts through the majority of the filter runs were generally low.

4.4 Direct Filtration Testing

An initial trial to evaluate performance of DF vs. conventional filtration was conducted from September 30 to October 11. During this test scenario, Train 1 was operated in DF mode while Train 2 was operated in conventional filtration mode, as shown in Figure 4-61.

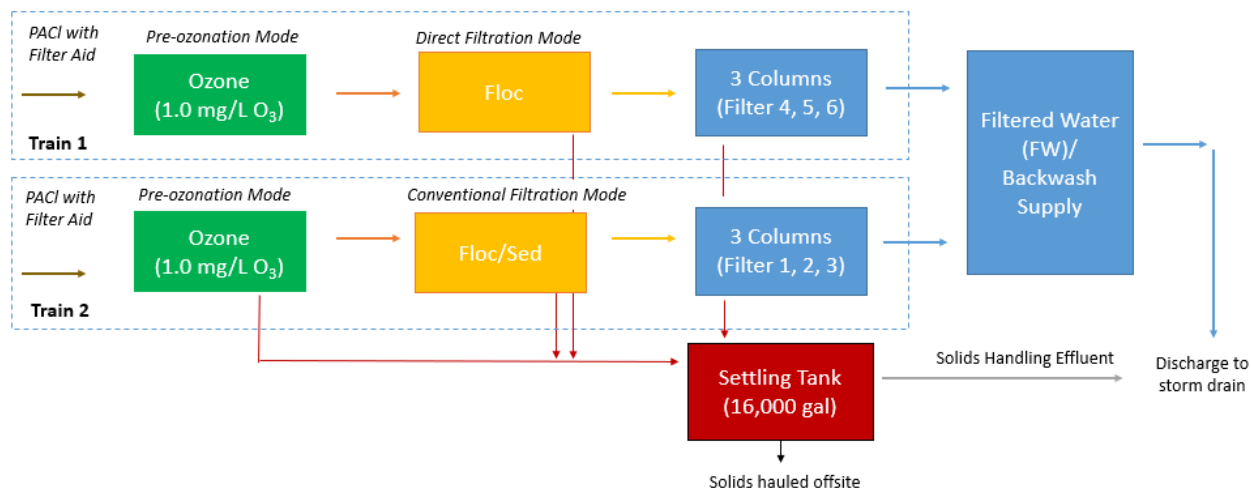


Figure 4-61. Treatment train for direct filtration treatment evaluation

(September 30 through October 11)

During the DF trial, coagulant and filter aid doses were maintained the same between the two treatment trains. For the first 3 days of the test, both Train 1 and Train 2 were dosed with 3 mg/L of PACI. On October 4, the PACI dose was increased to 3.5 mg/L in both trains, where it was maintained for the remainder of the test.

Because the pilot plant trains had been configured to feed filter aid polymer to the settled water at the floc/sed modules, an alternate filter aid feed point was needed when Train 1 was switched to DF mode. Initially, filter aid was fed to Flocculation Basin 3 in Train 1, which was the furthest downstream feed point available at the floc/sed modules when operating in DF mode. For consistency of operations, Train 2 was also modified to feed filter aid polymer at Flocculation Basin 3. On October 7, the filter aid polymer was moved to the filtration module for Train 1. It was fed at the filtration module for the remainder of this test scenario. The dosing location for Train 2 was moved back to the sedimentation outlet. The filter aid polymer dose was maintained at 0.01 mg/L throughout the test scenario. During the DF trial, focus was placed on maintaining similar operations between both trains, as opposed to optimizing coagulation in Train 1 for DF. However, this resulted in poor performance in Train 1. This can be seen in Figure 4-62, which presents the filter effluent turbidity from Filter 4 during the DF testing. These results are representative of observations from all three of the Train 1 filters during the direct testing evaluation. While it was hypothesized that coagulation conditions optimized for conventional filtration might result in larger floc that would blind the filters when operating in DF mode, what was observed was that turbidity rapidly broke through the filters, resulting in short filter runs. It is possible that the larger flocs, which would have settled during conventional filtration, instead sheared into smaller fragments when sent directly to the filters. While there are not sufficient data to determine the mechanism for failure, what is clear is that the coagulation conditions tested were not suitable for DF. Further testing would be necessary to adequately evaluate DF.

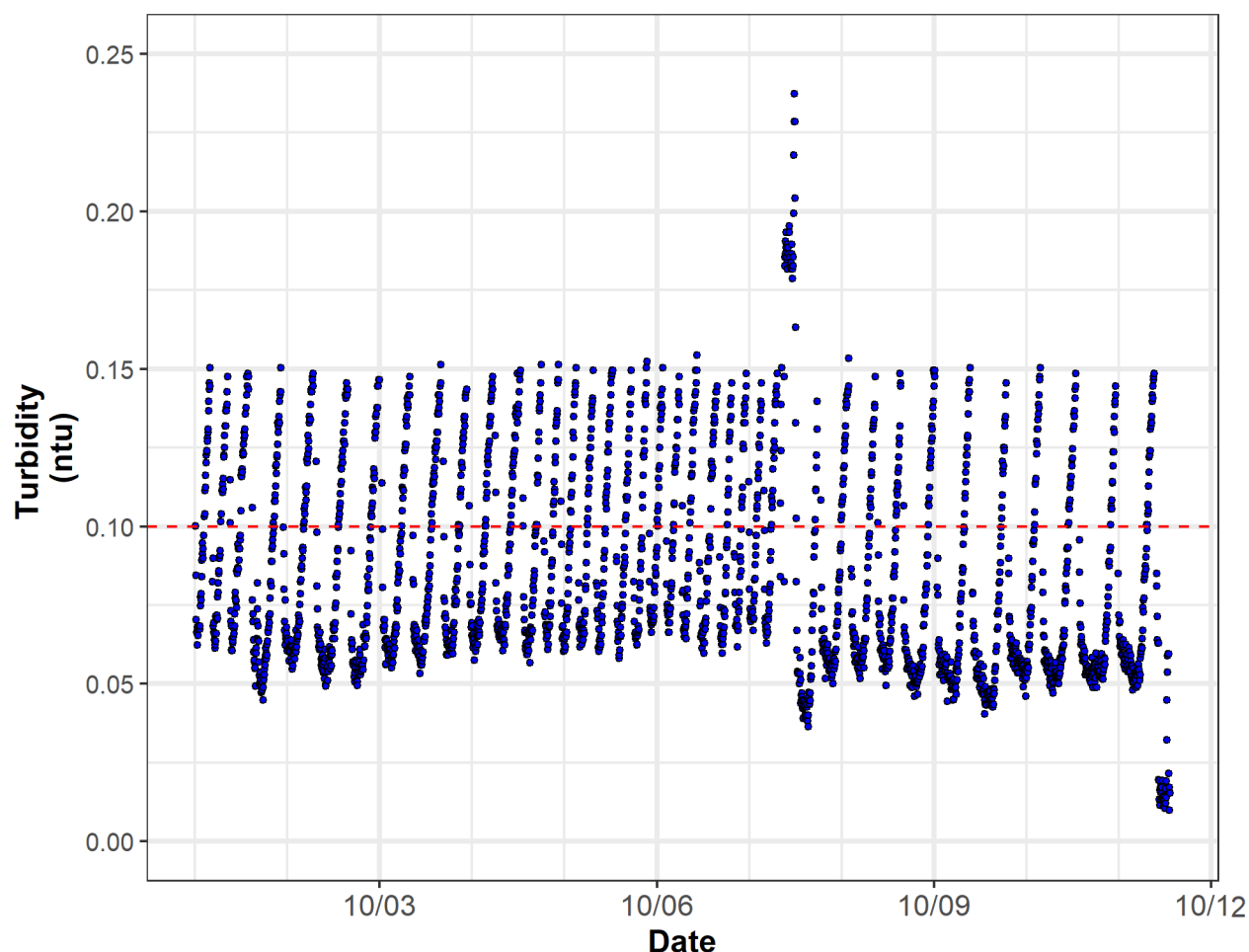
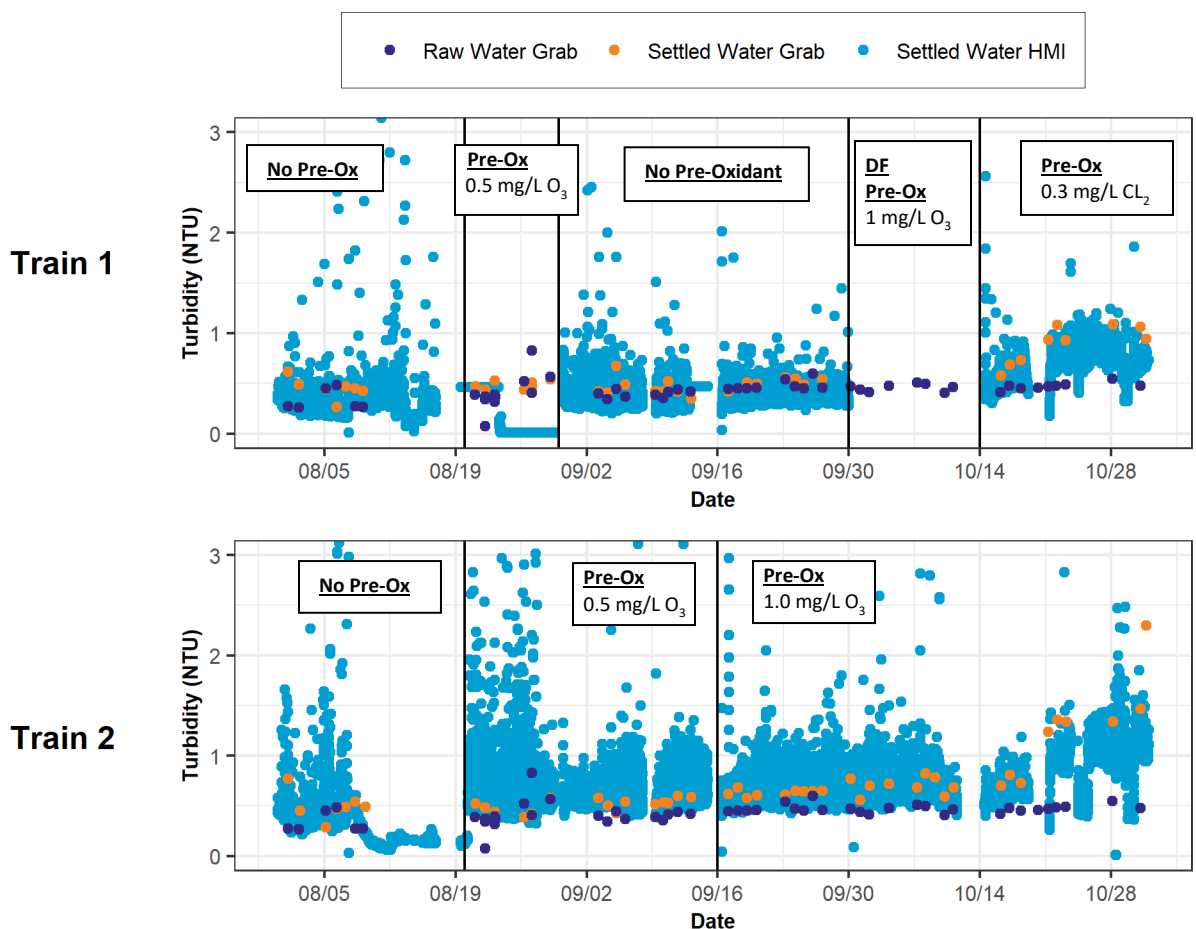


Figure 4-62. Turbidity values from Filter 4 (Train 1) during the direct filtration trial, from October 1 - October 11

4.5 Settled Water Quality

Settled water turbidity data are presented on Figure 4-63 showing the data from online turbidimeters after the sedimentation basins for each train (Settled Water HMI), recorded at a five-minute interval along with grab sample data collected daily during the week. The settled water turbidity is compared to the raw water turbidity grab samples in Figure 4-63. During the testing period for DF from September 30 to October 11, the sedimentation basin was offline, therefore the data collected from the Train 1 turbidimeter were removed from the data set, given the meters were measuring stagnant water. Turbidity grab samples were collected from the floc basin effluent during the DF trial, however the operation was not considered representative of a direct filtration mode, as discussed in Section 4.4, and therefore the grab samples were not presented for this period. In addition, a period with intermittent operation occurred from August 12 to 20 due to mechanical issues with the ozone module, during which time grab samples were not collected.

During the testing period settled water turbidity had the potential to be influenced by the presence or absence of pre-oxidation. The number of plates in the sedimentation basins, and the corresponding SLR was maintained at 0.3 gpm/sf during the testing period, so there was no influence on turbidity as a result of SLR changes. Settled water quality will be further evaluated and discussed in the next phase of testing with changes to the SLR and filtration rates.



Settled and Raw Water Turbidity between 2019-07-31 & 2019-11-01

Figure 4-63. Comparison of settled and raw water turbidity in Train 1 and Train 2 from July 31 - Oct 31

Despite the variation in pre-oxidation, the settled water turbidity grab samples remained relatively stable under 1 NTU through mid-October in both trains, and generally aligned with the raw water samples. Settled water turbidity trended upward around October 18, deviating from the raw water, which correlates to when the filter performance decreased. The settled water turbidimeters measured a wide range of turbidity with the grab samples trending toward the lower end of the HMI turbidity measurements. This is expected given the short measurement frequency, which picks up temporary changes not observed in the grabs. There were also some periods when communication between the turbidimeter and HMI were interrupted, as indicated by the flat settled water HMI turbidities shown in Figure 4-63.

Aside from settled water turbidity, settled water particle count data were reviewed to assess the impact of pre-oxidation on settled water quality. Settled water particle counts are limited to Train 1, which is the only floc/sed module with a particle counter. Figure 4-64 presents settled water particle count data collected during this period from Train 1.

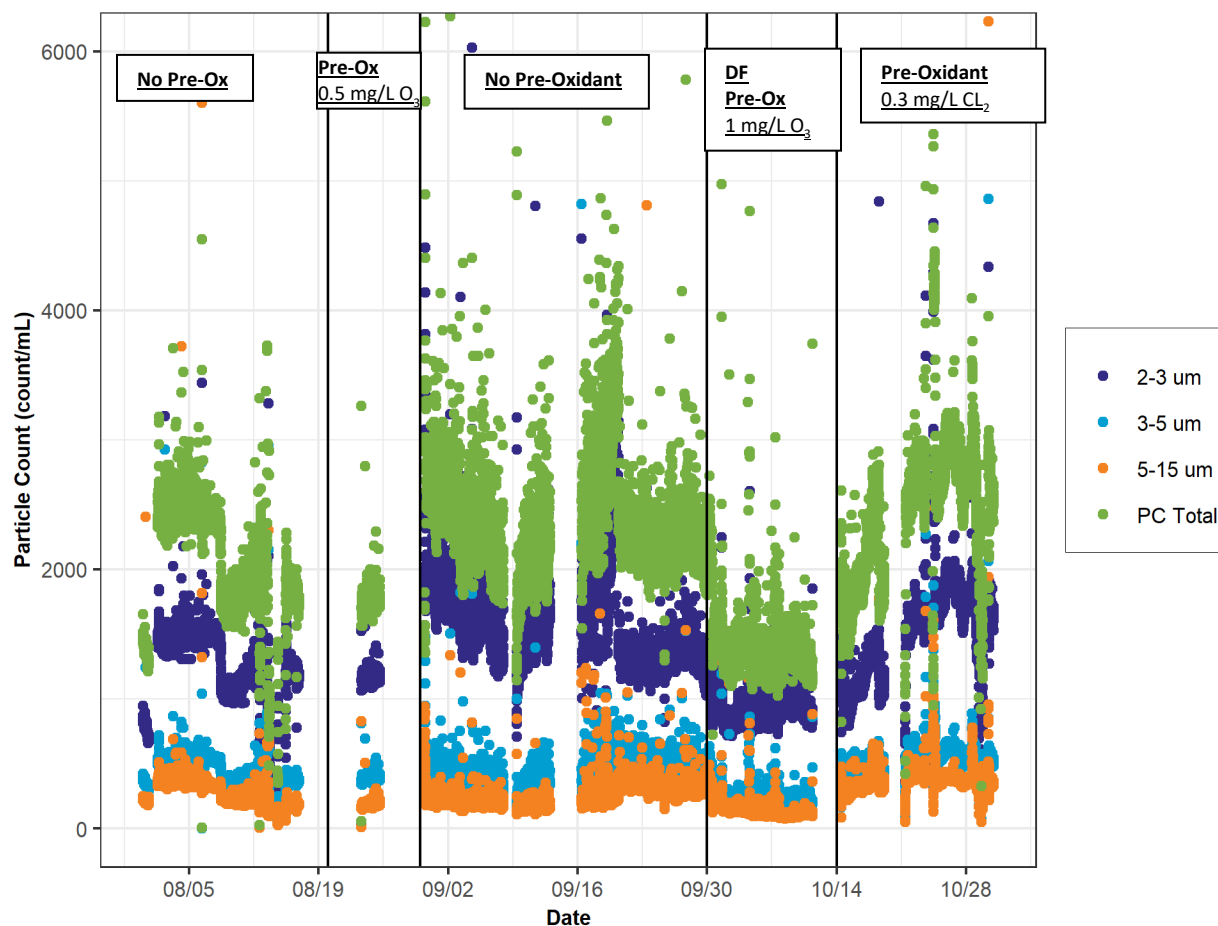


Figure 4-64. Settled water particle counts from July 31 to October 31

Settled water particle counts trended similar to the floc sed inflow (Section 3.3), with the exception of the period from September 16 to 30, during which the floc sed inlet total particle counts increased more substantially. The settled water particle counts demonstrated the same overall decrease when compared to the floc sed inlet from September 30 to October 14, when the pre-ozonation dose was applied at 1.0 mg/L O_3 . The particle counts within all size ranges in the settled water increased again after October 14 when the pre-oxidant changed to chlorine at a dose of 0.3 mg/L. Particle counts increased back to levels observed before the ozone dose of 1.0 mg/L O_3 was applied when there was no oxidant, indicating that the particle counts are more influenced by ozone at a higher dose compared to chlorine. Settled water particle counts will be further evaluated in the future testing periods with changes to SLR and filtration rates.

4.6 Summary

Pilot testing during this period began with an evaluation of four coagulants: PACl, alum, ferric chloride, and ACH. Of these four, alum and PACl performed well in terms of filter productivity and filter effluent quality. While there was little performance difference between alum and PACl, when alum was used it consumed raw water alkalinity, lowered coagulation pH, and required the addition of supplemental alkalinity in the form of sodium bicarbonate for effective treatment. Therefore, PACl was selected as the coagulant for subsequent pilot trials.

Pre-oxidation, in the form of ozone or chlorine, was found to increase filter productivity (as measured by UFRV) and to minimize filter effluent turbidity and particle counts during the majority of the run. However, it was also observed that filter runs following pretreatment with a pre-oxidant were characterized by a sharp particle breakthrough at the end of each filter run; similar behavior was not observed in the train with no pre-oxidant during the side-by-side pre-ozonation vs. no pre-oxidant trial. This particle breakthrough may be attributable to pre-oxidation, or it may be influenced by other treatment parameters such as the filter aid polymer dose applied to both trains. Future testing will evaluate the breakthrough of particles at the end of filter runs to determine the controlling water treatment parameters.

Direct filtration was briefly evaluated during this test period. During the DF trial, coagulant and filter aid doses in the DF train were maintained the same as those in the conventional treatment train with sedimentation. While these coagulant conditions were effective in the conventional treatment train, they did not result in successful filter runs during DF operation. Further efforts to optimize operations for DF were not made during this test period.

Settled water turbidity and particle counts during this test period were relatively consistent, and largely unaffected by process condition changes such as the presence or absence of pre-oxidation. Settled water turbidity did increase at the end of October, which coincided with a period of shortened filter runs.

Chapter 5

Filter Performance Comparison

This section provides a summary of performance across the various testing regimes, including a comparison of performance between filtration rates and filter media based on clean bed head loss (CBHL), UFRVs, and organics removal. Biological activity in the filters is also discussed in this section.

5.1 Clean Bed Head Loss

The theoretical CBHL calculations for July 1–December 3 are summarized in Table 5-1. Figure 5-1 summarizes the initial CBHL for the GAC and anthracite filters for the period of continuous operation from July 1–October 31. For the majority of the time, GAC filters had slightly higher CBHL, when comparing equivalent unit filtration rates. The large step up in CBHL observed on July 26, indicated by a vertical dashed line on Figure 5-1, corresponded to the transition from lower to higher filtration rates (6 to 8 gpm/sf and 8 to 12 gpm/sf for the 60-inch and 72-inch depth columns, respectively). When the transition in filter rates occurred, the CBHL increased by approximately 1.75 ft in the 72-inch depth columns and approximately 0.75 ft in the 60-inch depth columns.

Beyond the theoretical increase in head loss due to the filtration rate increase and temperature changes over this period of operations, the CBHL in all filters increased over time. This increase appears to be most significant in the two 72-inch GAC columns. The theoretical CBHL is calculated based on the media depth and media characteristics, along with the operating unit filtration rate and water temperature. The water temperature was obtained from Floc/Sed 1000 and Floc/Sed 2000 incoming water temperatures, recorded in five-minute increments and averaged for each period of operation presented, while the observed CBHL is an average of the recorded CBHL during those times. The number of observed CBHL values included in the average calculation varies between filters as well as time periods depending on the number of filter runs. For all filters, the observed CBHL is greater than the theoretical value when adjusted for unit filtration rate and temperature.

Table 5-1. Theoretical Clean Bed Head Loss

Filter	Date	Temperature (°C)	Loading Rate (gpm/sf)	Theoretical CBHL (ft)
1	7/1/2019	13.86	8.00	2.07
	7/26/2019	14.06		2.05
	7/26/2019		12.00	3.08
	10/31/2019	10.90		3.36
2	7/1/2019	13.86	6.00	1.52
	7/26/2019	14.06		1.52
	7/26/2019		8.00	2.02
	10/31/2019	10.90		2.20
3	7/1/2019	13.86	8.00	2.11
	7/26/2019	14.06		2.10
	7/26/2019		12.00	3.15
	10/31/2019	10.90		3.43
4	7/1/2019	13.86	8.00	2.11
	7/26/2019	14.06		2.10
	7/26/2019		12.00	3.15
	10/31/2019	10.90		3.43
5	7/1/2019	13.86	6.00	1.51
	7/26/2019	14.06		1.51
	7/26/2019		8.00	2.01
	10/31/2019	10.90		2.20
6	7/1/2019	13.86	8.00	2.07
	7/26/2019	14.06		2.05
	7/26/2019		12.00	3.08
	10/31/2019	10.90		3.36

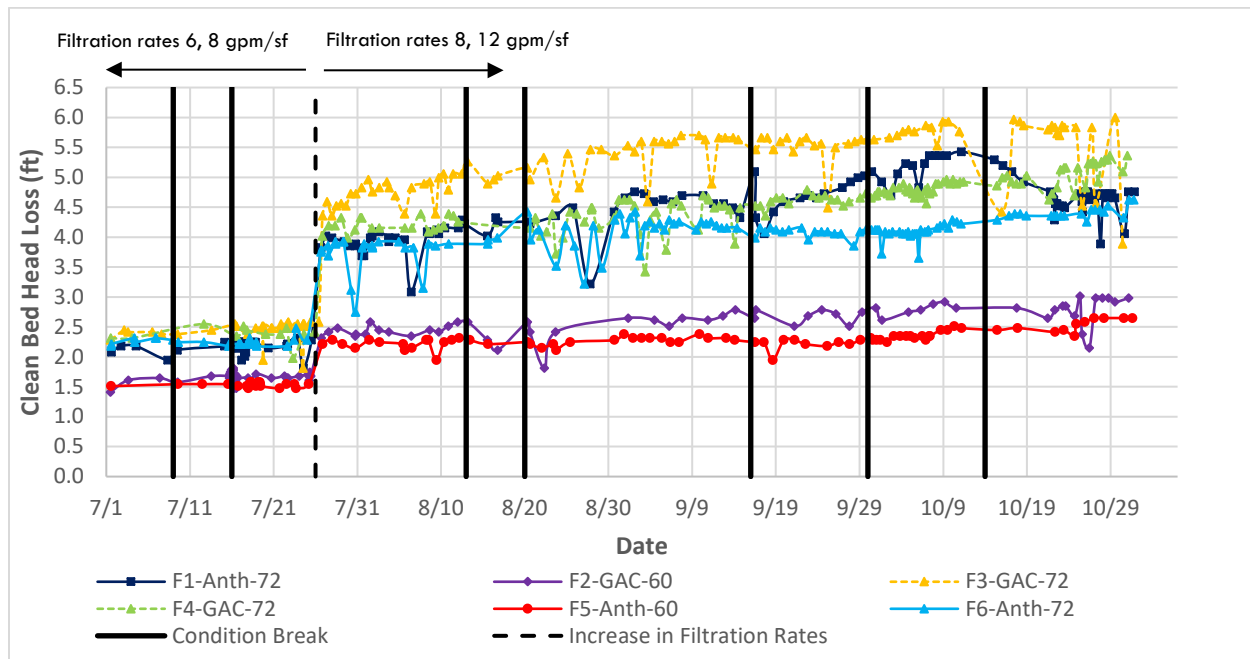


Figure 5-1. Clean bed head loss throughout the testing period for acceptable filter runs from July 1 - October 31

Filtration rate change on July 26 from 8 gpm/sf to 12 gpm/sf for Filters 1, 3, 4, and 6
and from 6 gpm/sf to 8 gpm/sf for Filters 2 and 5

A notable increase in the CBHL in Filter 1 was also observed starting around mid-September; however, after peaking around October 11, the CBHL in Filter 1 decreased to a range similar to that of Filter 6, the other 72-inch anthracite filter. The CBHL also increased in Filter 2, the 60-inch depth GAC column, but only by 0.24 ft. The 72-inch depth anthracite columns' CBHL also increased more than expected, with an average increase of 0.48 ft.

Overall, the observed CBHL was greater than the theoretical CBHL for all filters. However, there was a larger percent difference from the theoretical CBHL for the GAC filters (between 45 to 81 percent) compared to the anthracite filters (12 to 54 percent) throughout the three testing periods. This is attributable to the smaller effective size in the silica sand media used with the GAC filter columns.

CBHL is an important filter parameter because head loss is one of the thresholds used to determine when filters need to be backwashed. If the filters are operated identically and accumulate head loss at the same rate, filters with that start with the higher CBHL will have shorter run times, because they will hit the backwash threshold sooner. Additional testing will be used to investigate the cause for the increase in CBHL over time, as well as the divergence in CBHL between filters.

5.2 Turbidity

Turbidity data for the operational period is summarized in a box-whisker plot in Figure 5-2. All of the filters produced excellent water quality. The 8 and 12 gpm/sf GAC filters (Filters 2 and 3) had similar performance. The 8 gpm/sf anthracite filter (Filter 5) had a slightly better performance than the 12 gpm/sf anthracite filter (Filter 6) on Train 1. Filter 1 had higher turbidity than the rest of the filters.

This filter's turbidimeter has also required the most attention. It is believed that the higher turbidity on Filter 1 is more a fact of the turbidimeter complications than the pretreatment and filter design.

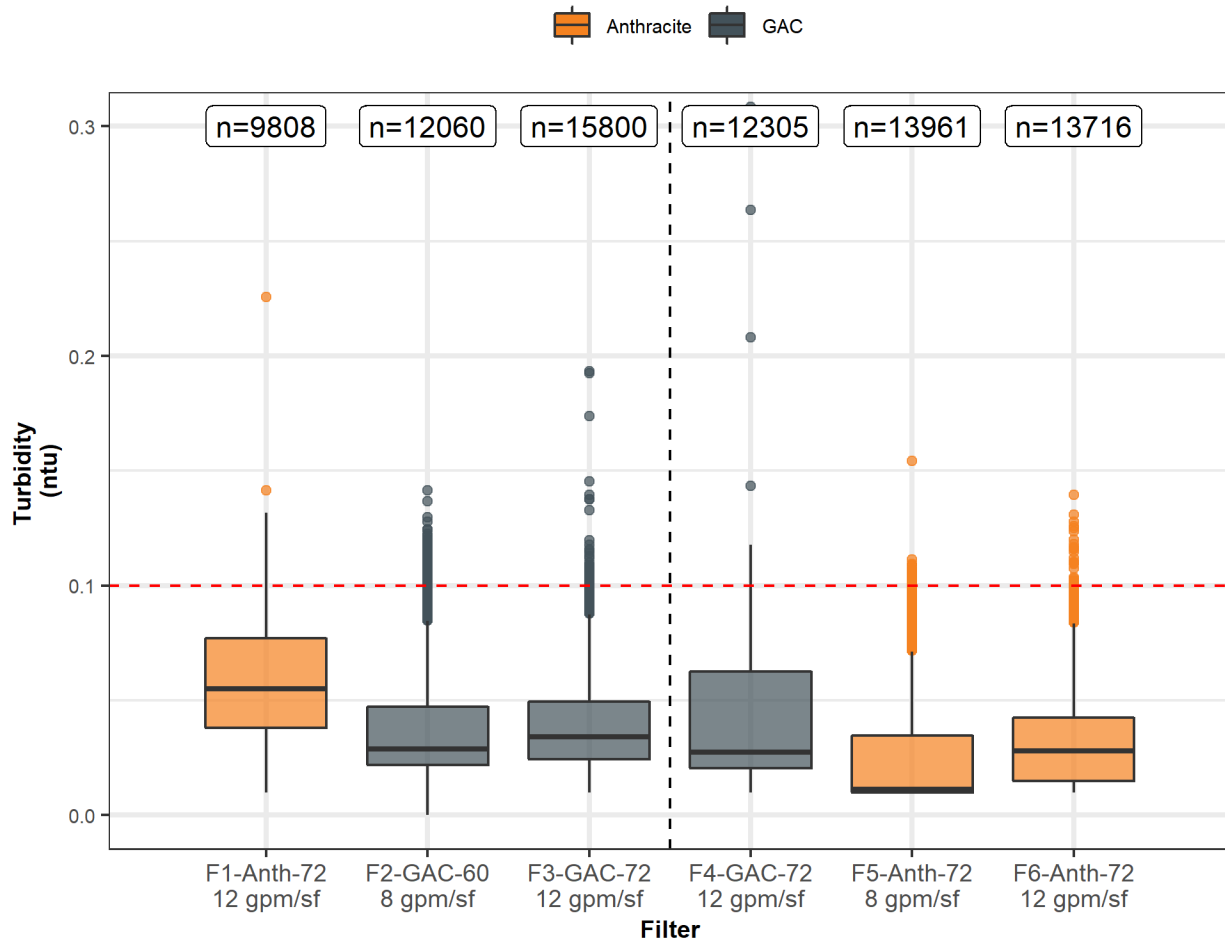


Figure 5-2. Turbidity for all filters from July 26 - October 18

Tables 5-2 and 5-3 present the turbidity data for each filter for the summer and fall seasons. The summer season covers operation from the beginning of July through the end of September. Table 5-3 presents the month of October. Additional fall season data will be presented in the Final Pilot Study Report. The 95th percentile data presented represents the 95th percentile of all the turbidity data from the accepted filter runs.

All of the 6 filters met the water quality goal in the summer and fall seasons to have the 95th percentile turbidity in the individual filter effluent be less than 0.1 NTU. Tables 5-2 and 5-3 show how Filter 1 had higher turbidity data than the other five filters.

Table 5-2. Filter Turbidity During Summer Season (July-Sep)

Combined FE MCL	95% of samples < 0.3 NTU					
Individual FE PSW Goal	95% of samples < 0.1 NTU					
Filter Number–Media–Depth	F1–Anth–72	F2–GAC–60	F3–GAC–72	F4–GAC–72	F5–Anth–60	F6–Anth–72
Filter Loading	12 gpm/sf	8 gpm/sf	12 gpm/sf	12 gpm/sf	8 gpm/sf	12 gpm/sf
50th Percentile	0.053	0.026	0.029	0.029	0.013	0.026
95th Percentile	0.095	0.074	0.061	0.073	0.049	0.063
Number of Samples	7,349	8,896	12,281	11,363	13,279	12,776

Note: Turbidity data presented is based on HMI recorded samples taken every 5 minutes. Data covers the operational period from July 26th through September 30th.

Table 5-3. Filter Turbidity During Fall Season (Oct)

Combined FE MCL	95% of samples < 0.3 NTU					
Individual FE PSW Goal	95% of samples < 0.1 NTU					
Filter Number–Media–Depth	F1–Anth–72	F2–GAC–60	F3–GAC–72	F4–GAC–72	F5–Anth–60	F6–Anth–72
Filter Loading	12 gpm/sf	8 gpm/sf	12 gpm/sf	12 gpm/sf	8 gpm/sf	12 gpm/sf
50th Percentile	0.059	0.049	0.053	0.015	0.010	0.045
95th Percentile	0.098	0.093	0.089	0.045	0.046	0.054
Number of Samples	2,591	3,802	3,491	942	1,074	940

Note: Turbidity data presented is based on HMI recorded samples taken every 5 minutes. Data covers the operational period from October 1st through October 31st.

5.3 UFRVs

UFRVs are summarized in Figure 5-3 in a box and whisker plot to show the range of UFRVs for each filter throughout operations from July 26–October 18, during which period the filters operated at 8 gpm/sf (Filters 2 and 5) or 12 gpm/sf (Filters 1, 3, 4, and 6). When you compare the same filter designs (Filters 1 and 6, and Filters 3 and 4) between Trains 1 and 2, Train 2 has better performance than Train 1. On average, the filters operating at 8 gpm/sf had higher UFRVs than the filters operating at 12 gpm/sf. All of the filters' median exceeded a UFRV of 10,000 gal/sf-run. Except for filter 1, all of the filters' minimum value of the representative filter runs was above the UFRV goal of 6,500 gal/sf-run.

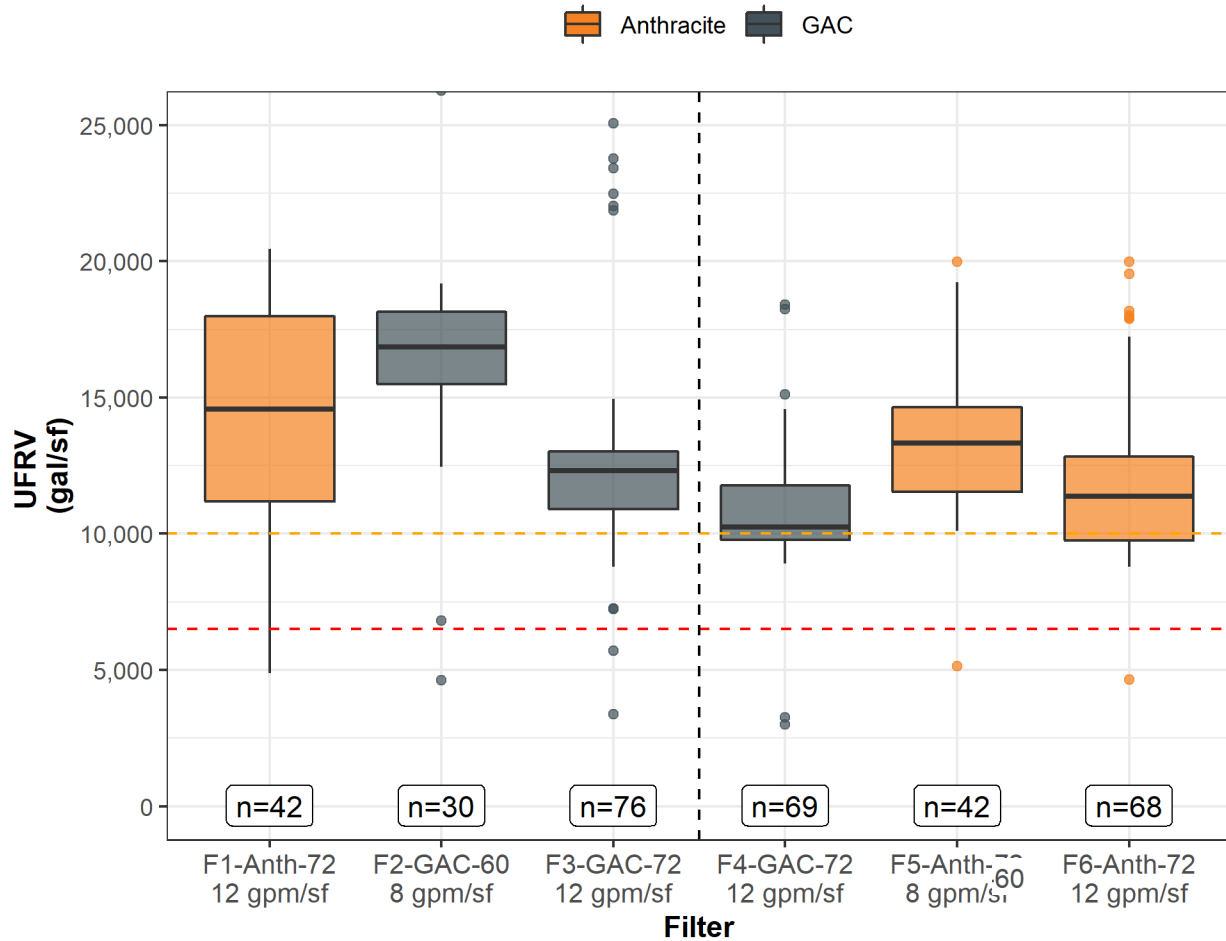


Figure 5-3. UFRV for all filters from July 26 - October 18

It is difficult to draw specific conclusions from Figure 5-3 beyond broad generalizations, because many different test periods and operating schema are represented in the figure. However, a couple of observations do stand out. The two filters that were operated at 8 gpm/sf (Filters 2 and 5) each had the highest median UFRVs for their train. Therefore, even though the pilot has so far demonstrated that the filters can produce high-quality filter effluent at 12 gpm/sf, this rate may not be optimal from a filter productivity standpoint. It is also notable that the two 72-inch depth GAC filters had the most variability between filter runs on their trains. Based on this data set, it appears that the anthracite filters are more consistent than the GAC filters, in general.

5.4 Organics Removal

Organics removal in filters from the same train with the same media, but differing filtration rates (Filters 2 and 3 for Train 2 and Filters 5 and 6 for Train 1) are compared to understand if there was an impact on performance as a result of the filtration rate. Filters 1 and 3 and Filters 4 and 6 are compared to understand the difference in performance due to the filter media.

5.4.1 Filtration Rate Comparison

The amount of TOC and UV₂₅₄ removed in Filters 2 and 3 and Filters 5 and 6 is presented in Figure 5-4 through Figure 5-7, respectively. During the pre-oxidant testing period (August 30–October 18), there were four distinct operating conditions.

From August 30–October 18, there was no consistent difference in TOC removal or UV₂₅₄ reduction between filters at 8 or 12 gpm/sf filtration rates.

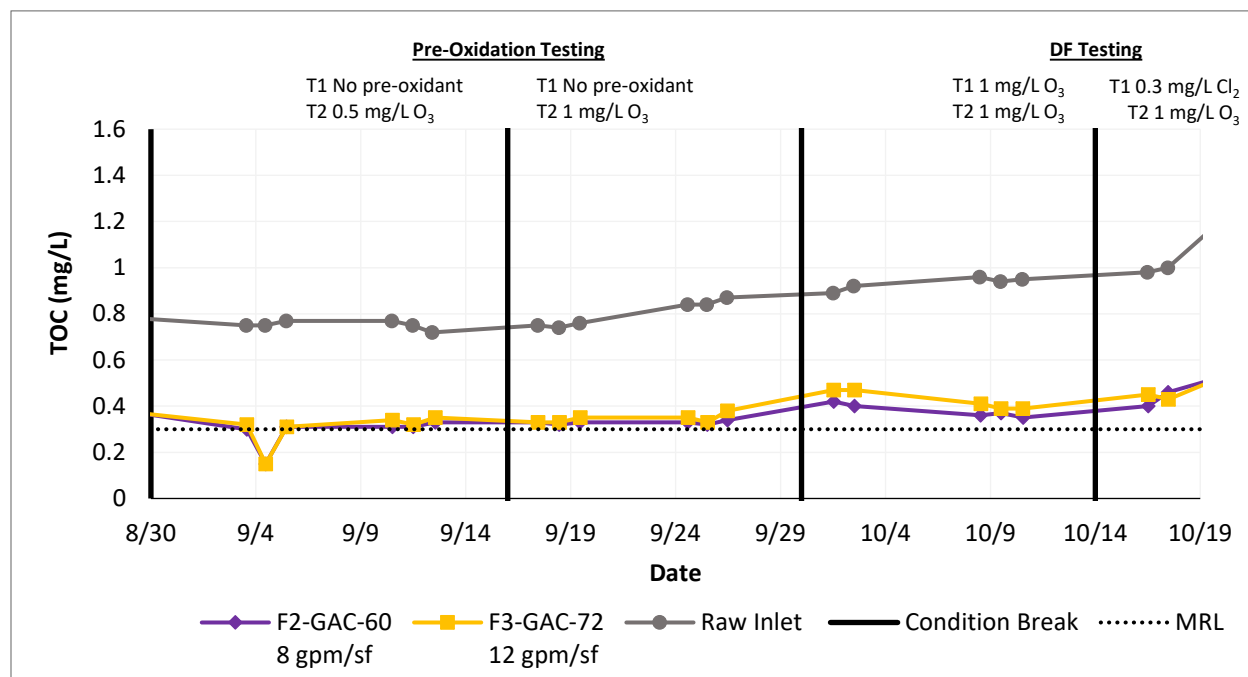


Figure 5-4. Organics removal for GAC filters (Filter 2 and Filter 3) - filtration rate comparison: TOC
TOC in Filter 2 and Filter 3 (Train 2 [T2]) effluent from August 30–October 18.

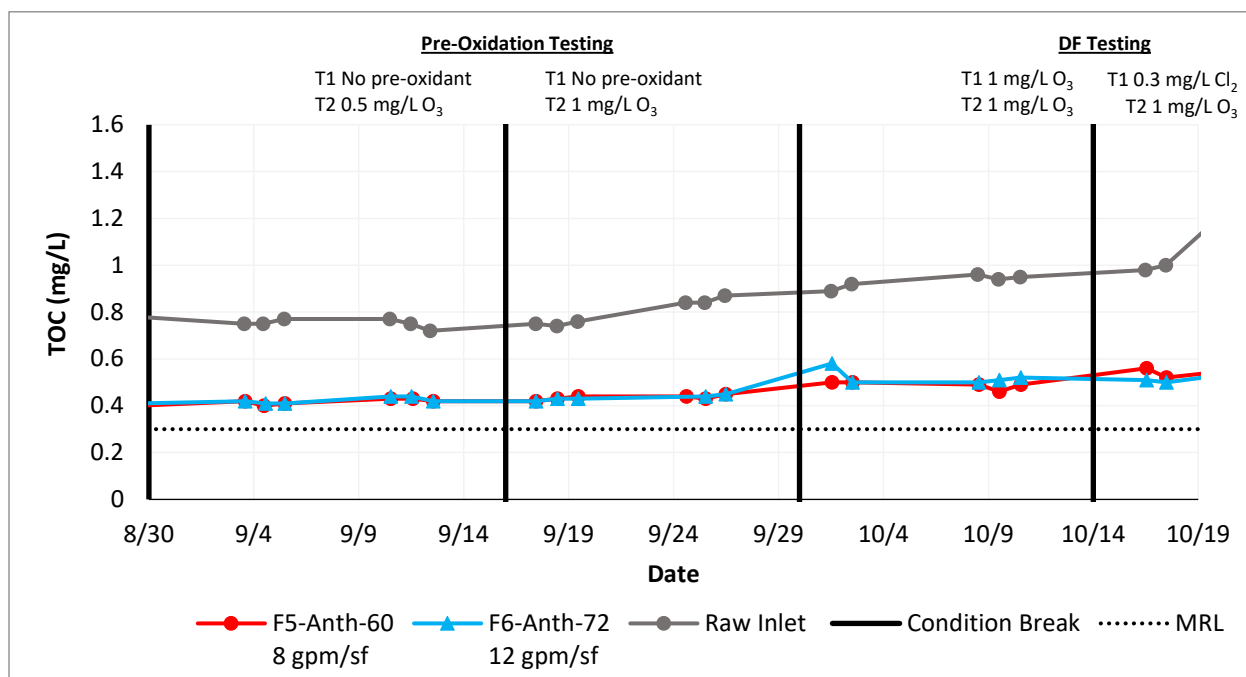


Figure 5-5. Organics removal for anthracite filters (Filter 5 and Filter 6) - filtration rate comparison: TOC
TOC in Filter 5 and Filter 6 (Train 1 [T1]) effluent from August 30-October 18.

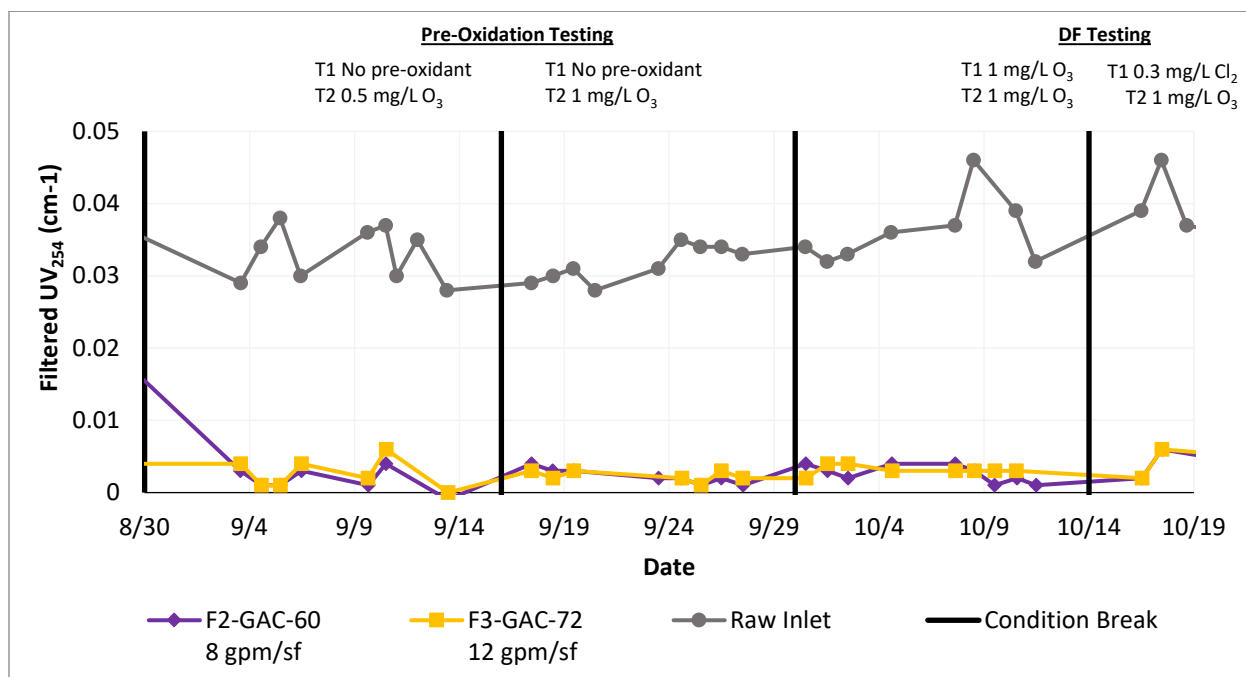


Figure 5-6. Organics removal for GAC filters (Filter 2 and Filter 3) - filtration rate comparison: Filtered UV₂₅₄
Filtered UV₂₅₄ in Filter 2 and Filter 3 (Train 2 [T2]) effluent from August 30-October 18.

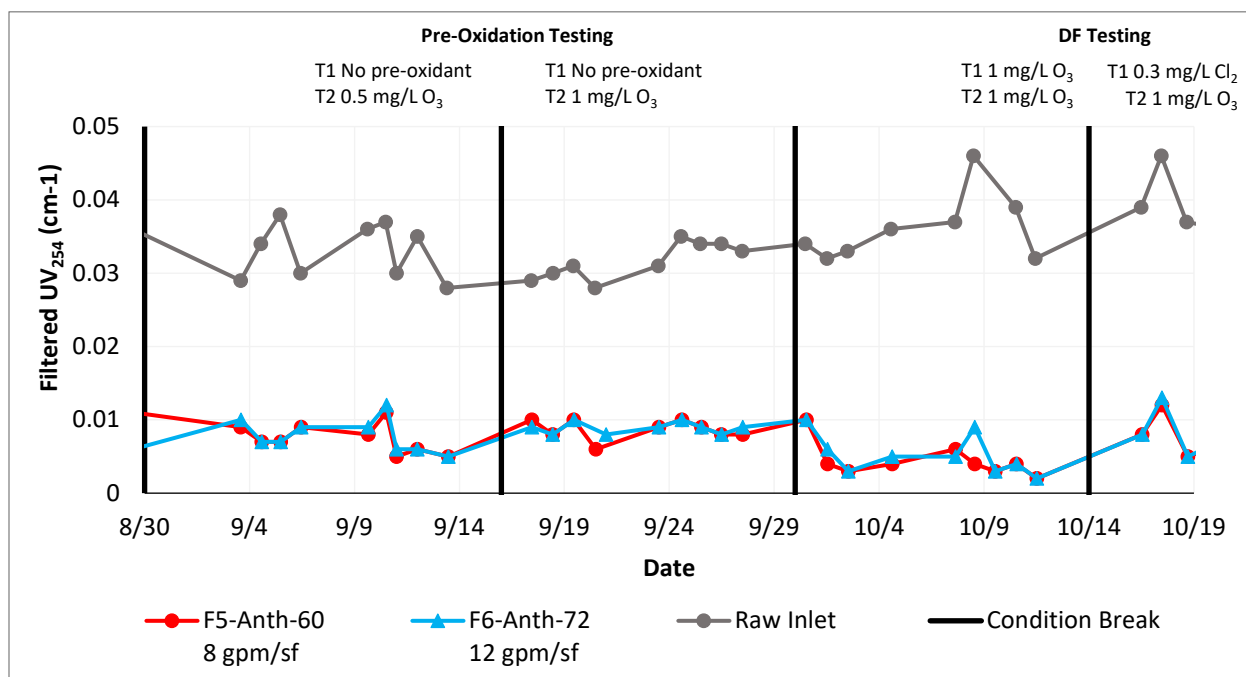


Figure 5-7. Organics removal for anthracite filters (Filter 5 and Filter 6) - filtration rate comparison: Filtered UV₂₅₄
Filtered UV₂₅₄ in Filter 5 and Filter 6 (Train 1 [T1]) effluent from August 30-October 18.

5.4.2 Filter Media Comparison

Organics removal is best compared within a single train, as different treatment conditions contributed to different organics removal between the two trains. The amount of TOC and UV₂₅₄ removed in Filters 1 and 3 and Filters 4 and 6 is shown in Figure 5-8 through Figure 5-11, respectively. TOC directly measures the concentration of organic matter present, while UV₂₅₄ reflects the nature of the organics that are present (recognizing that the structure of the organics in the filtered water is impacted by upstream treatment, including ozonation, so the UV₂₅₄ data is more qualitative than quantitative for this analysis).

The GAC filters (Filters 3 and 4) consistently removed more TOC and UV₂₅₄ than the anthracite filters (Filters 1 and 6), with the exception of Train 1 during the August 30 to September 30 time period. TOC removal in the GAC filters was between 0 and 24 percent more than the anthracite filters across the testing periods. Overall, UV₂₅₄ removal was greater than TOC removal for both media types.

Organics removal is also influenced by potential adsorption of organic compounds by the GAC, since virgin GAC was used for the pilot. Over time, as the media becomes exhausted and adsorption sites are occupied, organics removal through the GAC columns will be driven primarily through biological activity in the filter media.

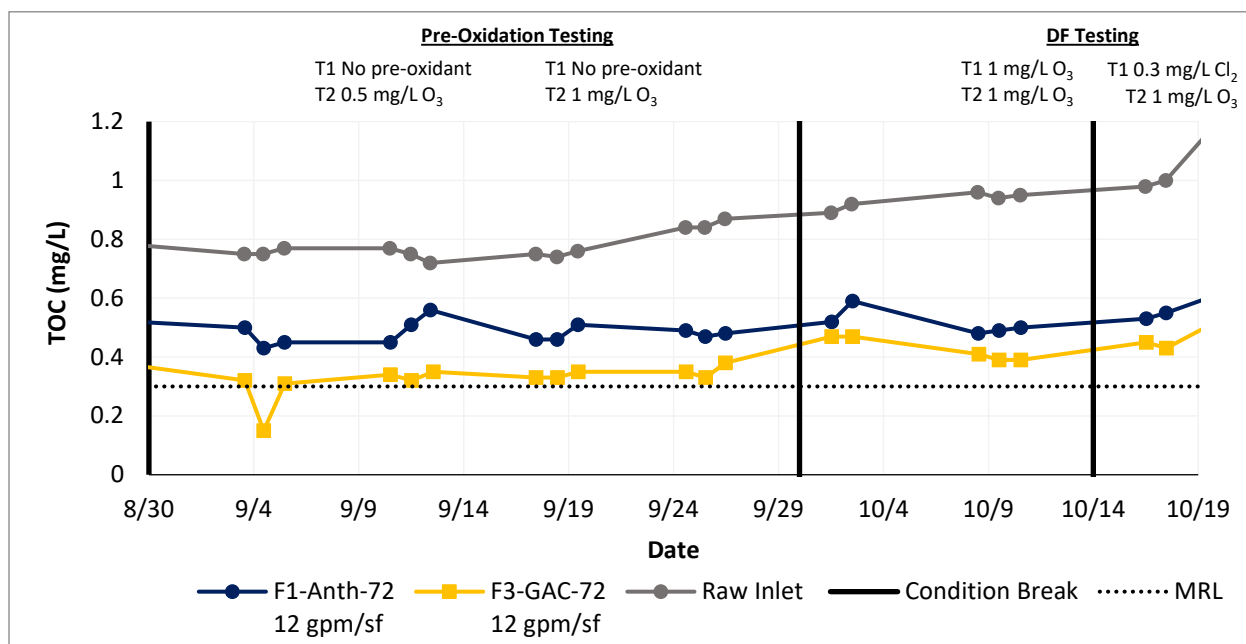


Figure 5-8. Organics removal for Filter 1 (Anth) and Filter 3 (GAC) – filter media comparison: TOC

TOC in Filter 1 and Filter 3 (Train 2 [T2]) effluent from August 30-October 31.

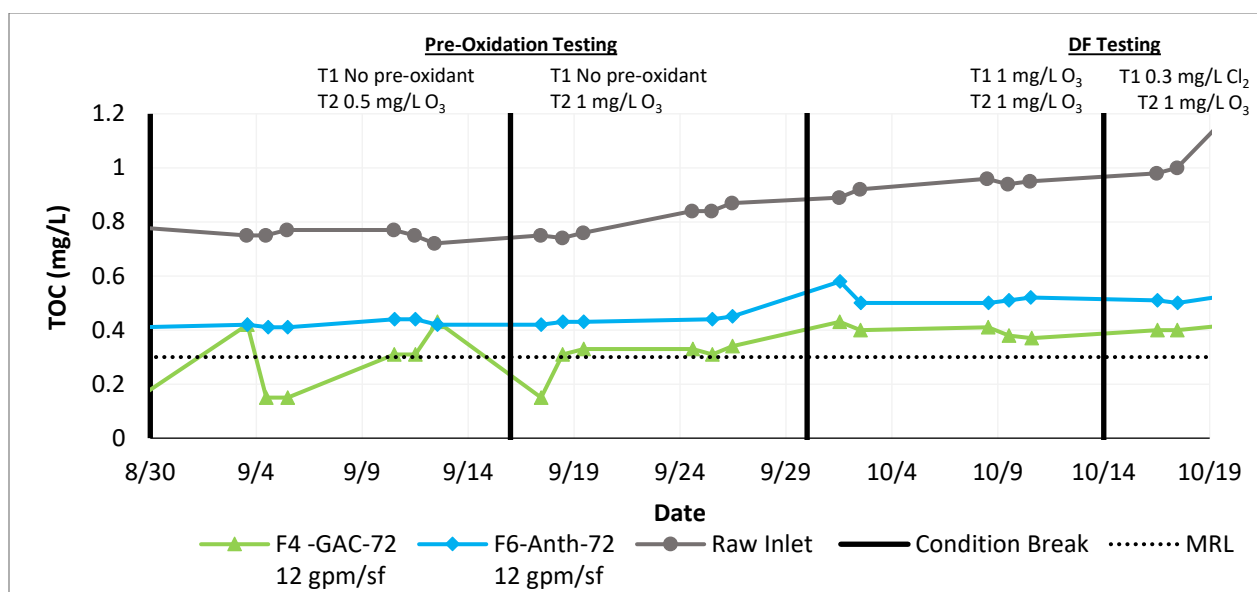


Figure 5-9. Organics removal for Filter 4 (GAC) and Filter 6 (Anth) – filter media comparison: TOC

TOC in Filter 4 and Filter 6 (Train 1 [T1]) effluent from August 30-October 18.

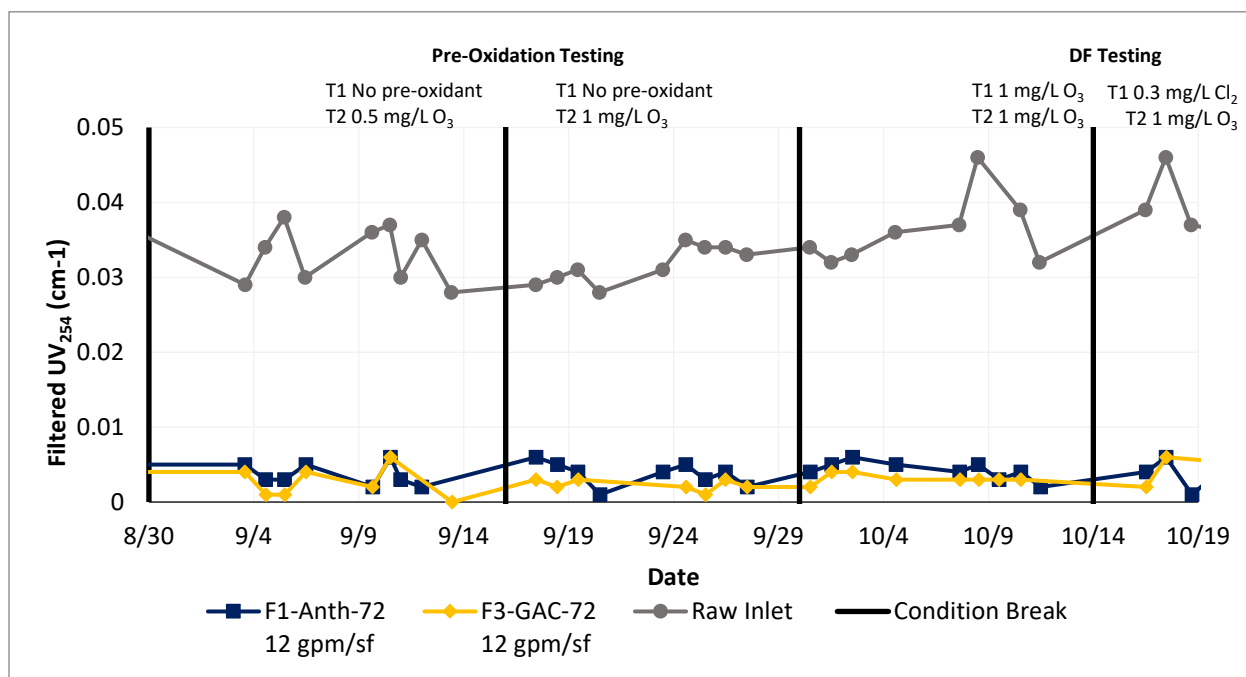


Figure 5-10. Organics removal for Filter 1 (Anth) and Filter 3 (GAC) – filter media comparison: Filtered UV₂₅₄
 Filtered UV₂₅₄ in Filter 1 and Filter 3 (Train 2 [T2]) effluent from August 30-October 18.

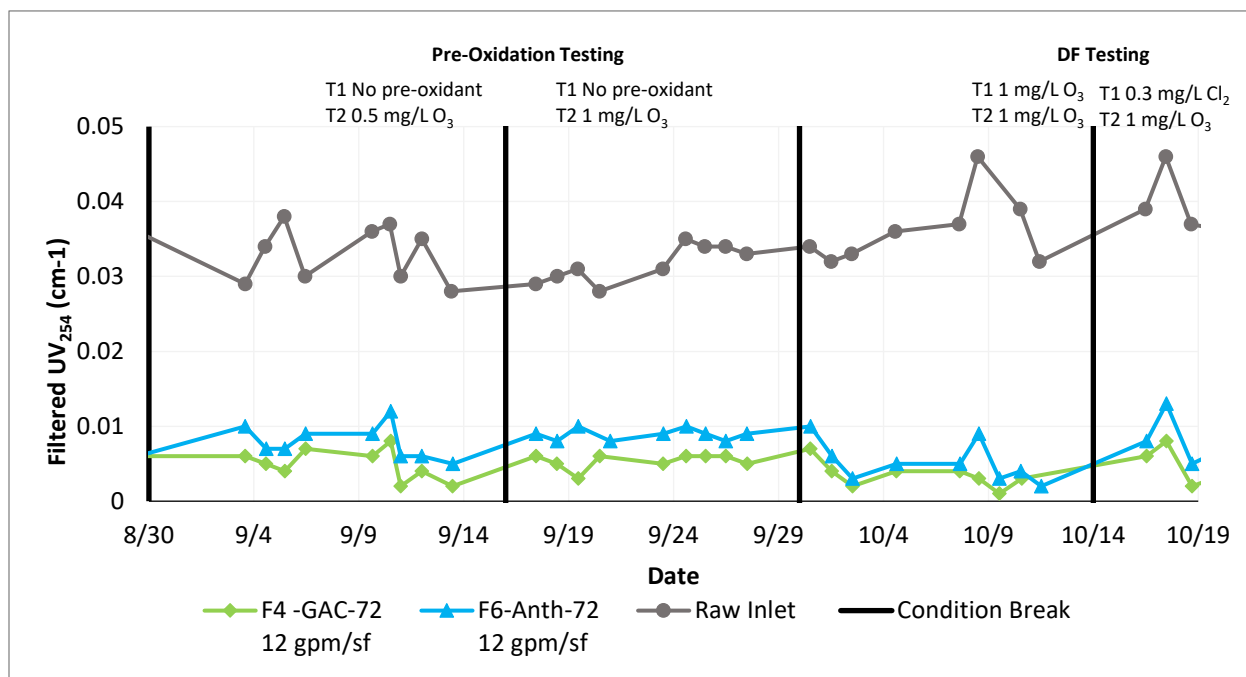


Figure 5-11. Organics removal for Filter 4 (GAC) and Filter 6 (Anth) – filter media comparison: Filtered UV₂₅₄
 Filtered UV₂₅₄ in Filter 4 and Filter 6 (Train 1 [T1]) effluent from August 30-October 18.

Overall the GAC filters removed more organics than the anthracite filters. However, the raw water organics levels are already considered to be very low when compared to other water supplies, and the observed organics removal in the anthracite columns generally averaged between 40 to 50 percent.

Therefore, even though the organics removal in the GAC filters was higher, the organics removal achieved by both media types is acceptable.

5.5 Biological Activity Monitoring

Biological treatment within a filter (i.e., a biofilter) at a drinking water treatment facility is an operational practice of managing, maintaining, and promoting biological activity on granular media in the filter to enhance the removal of organic and inorganic constituents before treated water is introduced into the distribution system. Naturally occurring biomass can accumulate when there is minimal to no chlorine residual in the filter influent. In biological filtration of most surface waters, aerobic respiration occurs and reduces organic compounds. Aerobic biofilters contain primarily heterotrophic bacteria, which use organic compounds as a substrate for growth (electron donor) and DO is consumed as an electron acceptor. Ozonation enhances biological filtration by creating a supersaturated DO condition and breaks down organic compounds to more readily biodegradable substrates.

This section describes monitoring techniques (namely adenosine triphosphate [ATP], carboxylic acids, and assimilable organic carbon [AOC]) to assess the amount of biological activity in the two pilot treatment trains.

5.5.1 ATP (Liquid and Media)

ATP is a semi-quantitative means to assess the amount of biological activity in a filter. ATP is a bioenergy molecule used in all living cells for energy transfer. ATP analysis was conducted using commercially available test kits from LuminUltra. Media ATP was monitored in the first sample port at the top of the filter media bed (approximately 6-inch media depth), and aqueous ATP was monitored in both the top of the filter media (approximately 6-inch media depth) and the bottom of the filter (midway through the sand layer).

The ATP filter media sampling results are presented in Figure 5-12 from sampling conducted on September 4. For comparison, filter media from eight different facilities in North America with biofiltration (including anthracite, GAC, and sand medias), ranged from 2,500 to 5.2 million picogram (pg) of ATP/g of dry filter media (Hooper et al. 2019). These filter media ATP levels in this pilot are on the lower side compared to the range of ATP media levels seen in these other full-scale biofiltration facilities. However, these full-scale facilities have been operating biofiltration for several years. Additionally, the ATP analysis presented was reflective of wet media instead of dry, which has the effect of artificially reducing the measured ATP levels. If the ATP levels were doubled (assuming a media moisture content of 50 percent), the observed levels in the pilot GAC filters would be comparable to ATP media levels observed at Halifax Water (~100,000 cATP/g dry media) (Hooper et al. 2019), which also has cold source water.

The GAC filters have a higher abundance of biological activity than the anthracite filters. This finding should be expected given that GAC media has much greater surface area to promote biological growth. During future pilot testing, biological activity will be further assessed with additional ATP media samples.

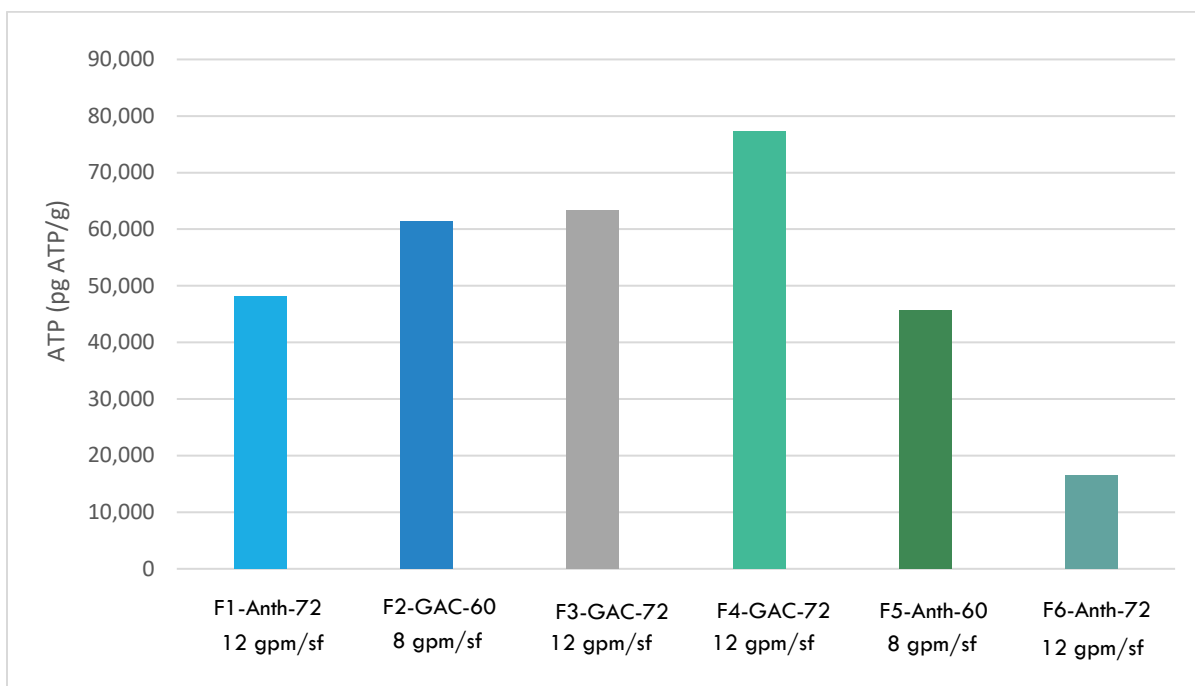


Figure 5-12. Filter media ATP sampling results-September 4

Aqueous ATP sampling results are presented in Figure 5-13. The hatched bars represent samples which were pre-ozonated. There is variability in the data captured from aqueous ATP sampling, which can be expected from liquid grab samples. ATP at the bottom of the columns has lower levels of biological activity when compared to the top of column. ATP is representative of biological activity and so it is expected to observe higher levels in the top and lower levels in the bottom of the filter column, but sloughing off of biomass could affect these results. Train 2 has slightly higher levels of ATP in the top of the columns. The GAC filters have higher levels of ATP in the top of the columns than the anthracite filters, which supports the filter media ATP data presented in Figure 5-12.

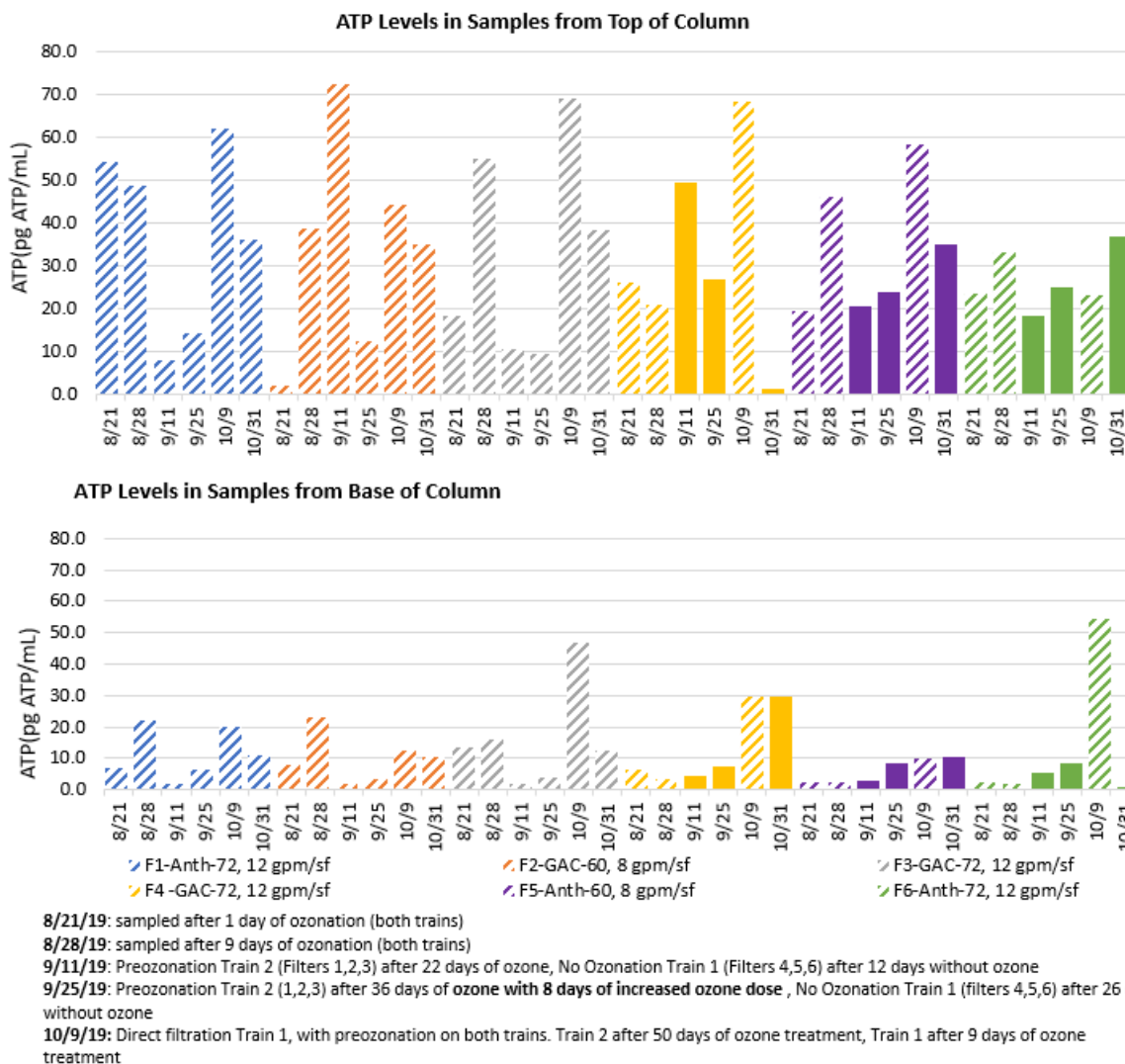


Figure 5-13. Aqueous ATP sampling results

Hatched bars indicate pre-ozonation

5.5.2 AOC Removal

AOC is a measure of organic material available for microorganisms to metabolize and serves as an indicator to represent bacterial regrowth potential in distribution systems. AOC is the fraction of DOC that can be easily assimilated by microorganisms and converted to cell biomass. Figure 5-14 shows the various forms of natural organic matter. Generally, for all natural organic matter (NOM), roughly 50 percent is TOC, and DOC is roughly 80 to 90 percent of the TOC fraction (Crittenden et al. 2012).

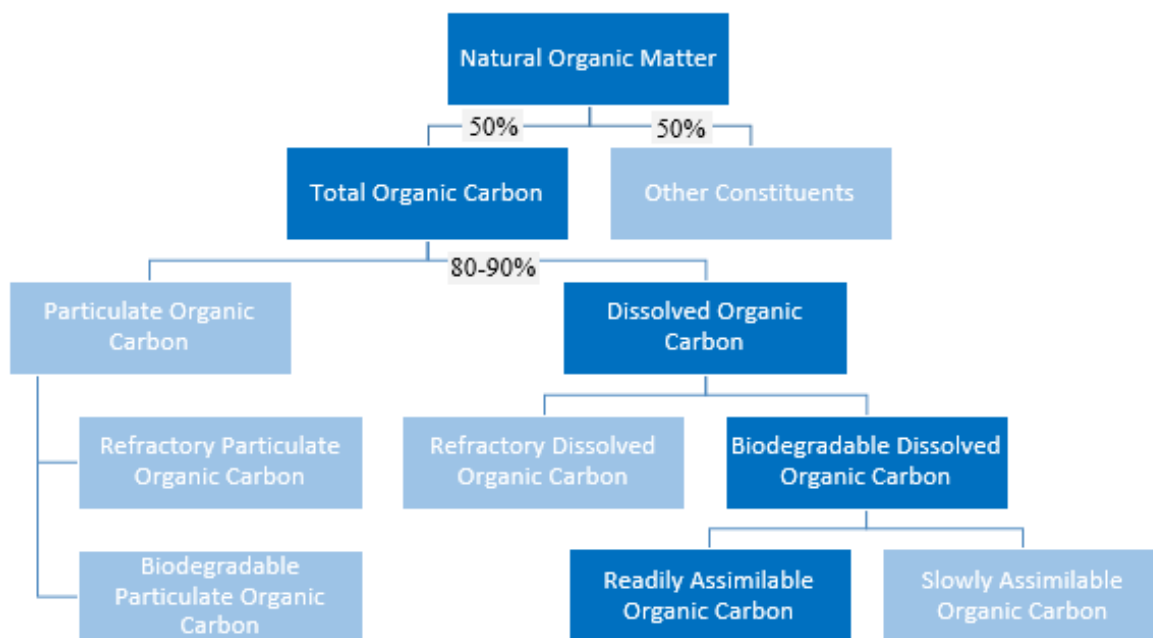


Figure 5-14. Forms of natural organic matter

(Adapted from Crittenden et al. 2012)

AOC data observed for this pilot are presented in Figure 5-15 and Figure 5-16 below. Figure 5-15 shows each sampling result for each test condition while Figure 5-16 presents a statistical summary of the data. In Figure 5-15, the hatched bars represent samples that were pre-ozonated. Ozonation increases the amount of AOC in the treatment process as it breaks down the organic carbon into more readily biodegradable substrates. When reviewing the 50th percentile of the AOC data (Figure 5-16), the filter effluent reduces the AOC concentration in the finished water from the raw water concentrations. Train 2, which operated with more ozonation, sees lower levels of AOC in the filtrate effluent and does a good job reducing the AOC concentrations, which is indicative of biomass acclimation. In Train 2, the 8 gpm/sf filter has lower AOC levels compared to the 12 gpm/sf filter with the same media.

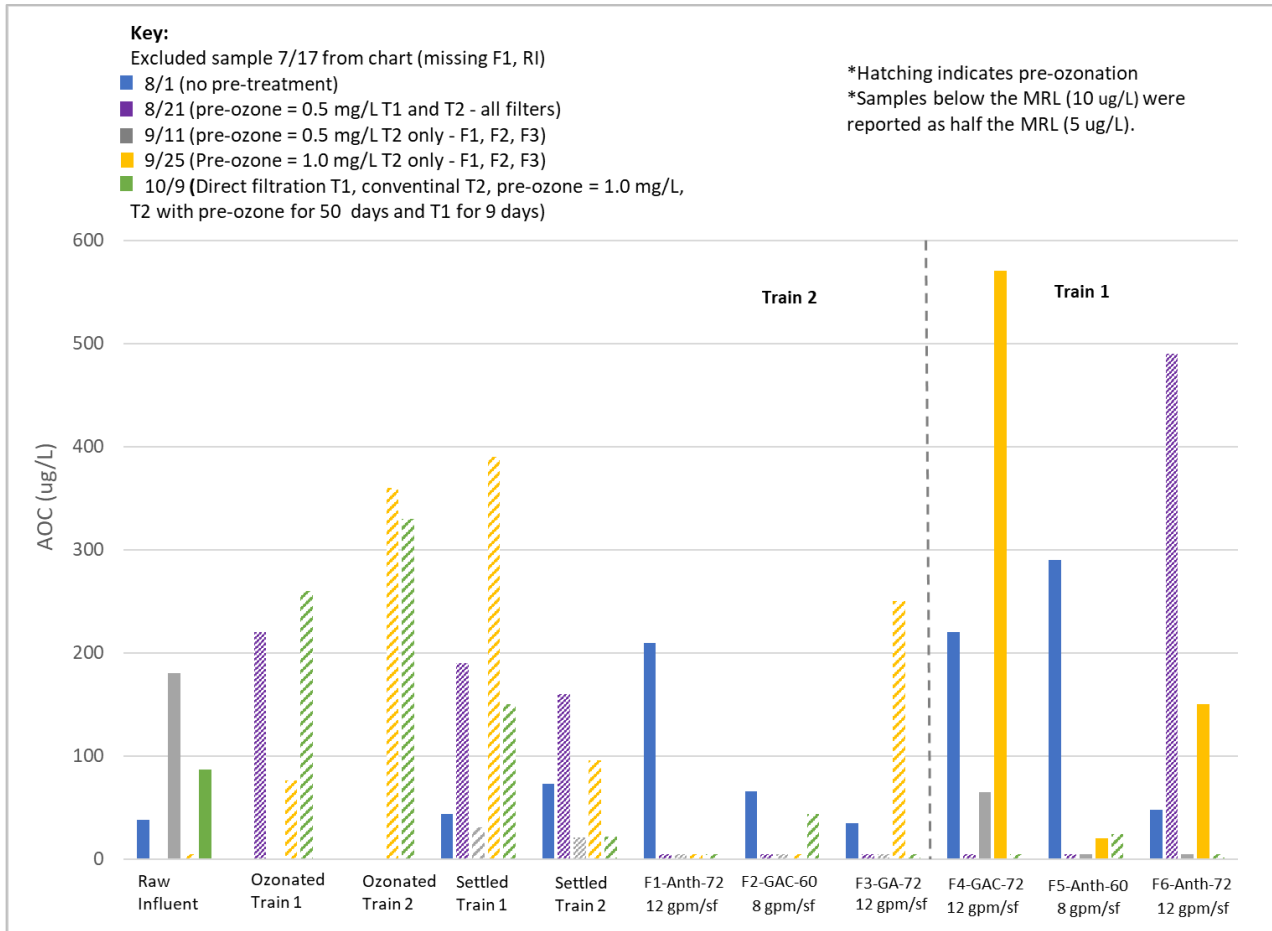


Figure 5-15. AOC data from each sampling point

Hatched bars indicate pre-ozonation

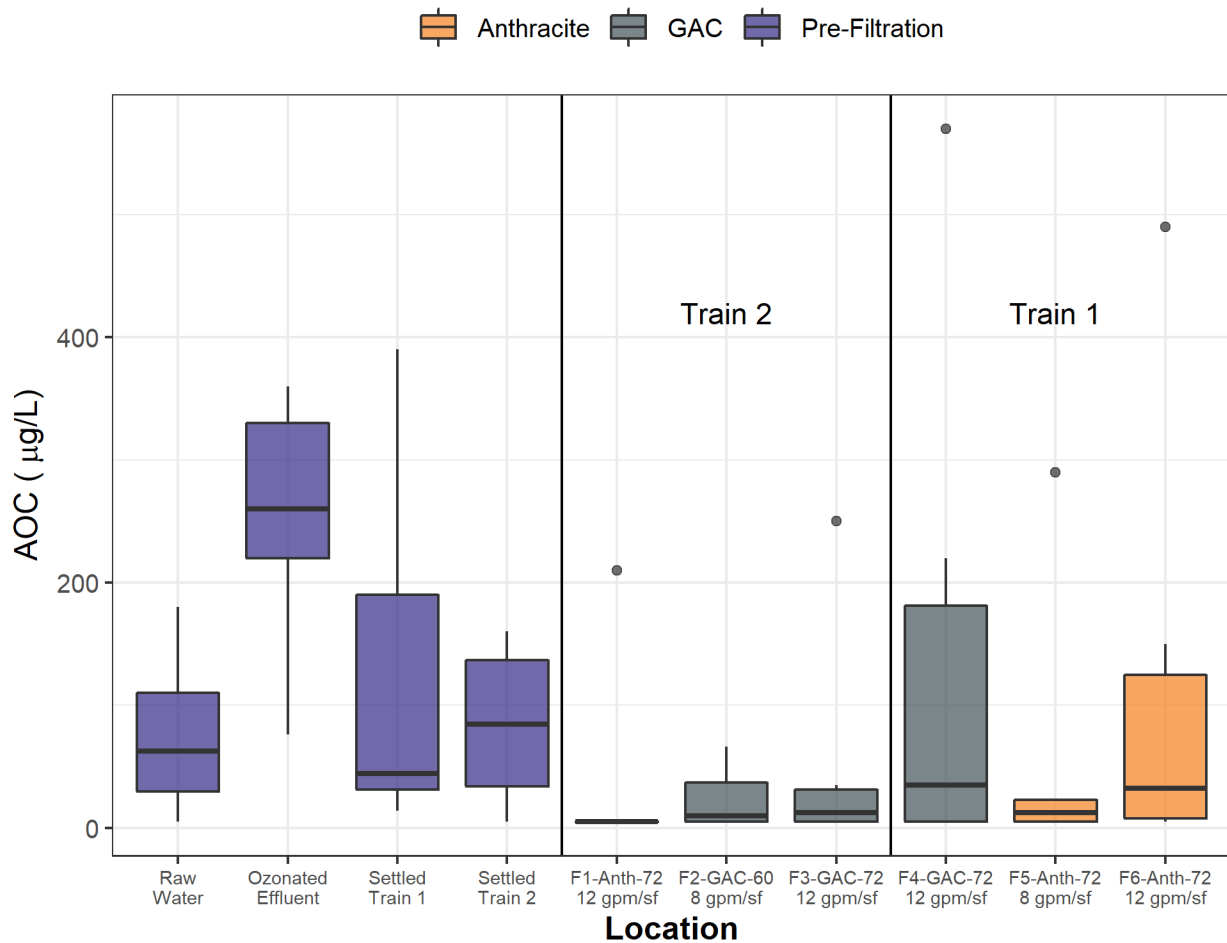


Figure 5-16. Statistical summary of AOC data

5.6 Summary

Several parameters were analyzed to evaluate overall filter performance during this test period. CBHL, which influences filter productivity, was found to be increasing over time in all filters. CBHL was highest in the 72-inch depth GAC filters (Filters 3 and 4), because those filters were operated at high filtration rates (12 gpm/sf) and had the tightest silica sand media distribution. Because these filters have the highest CBHL, their filter productivity may be lower than other filters if head loss is the factor controlling backwash frequency.

All of the filters had low levels of filtrate turbidity. All of the 6 filters met the water quality goal in the summer and fall seasons to have the 95th percentile turbidity in the individual filter effluent be less than 0.1 NTU.

Overall, it was found that the filters operated at 8 gpm/sf tended to have higher UFRVs than the filters operated at 12 gpm/sf. When comparing the combined dataset of filter runs from this test period for the filters operating at 12 gpm/sf, the anthracite filters had higher UFRVs than the GAC filters.

When comparing organics removal between filters, it appears that organics removal was largely unaffected by filtration rate. GAC media consistently removed more TOC than anthracite filters, with or without pretreatment with a pre-oxidant. This may be attributable to the fact that virgin GAC was used for the filters, so the adsorptive capacity of the GAC for TOC was not exhausted for much of the time frame included in this report. The differential in TOC removal between the anthracite and GAC filters decreased over the duration of the test period, suggesting that the adsorptive capacity of the GAC may have begun to diminish as available adsorption sites were occupied.

As expected, biological activity was highest in the GAC filters. Train 2, which operated with more ozonation, sees lower levels of AOC in the filtrate effluent and does a good job reducing the AOC concentrations, which is indicative of biomass acclimation.

Chapter 6

Chlorine Demand/Decay and DBP Testing

The Work Plan includes a series of SDS tests throughout the 12-month pilot testing period to evaluate the effect of filtration and various treatment approaches on the formation of DBPs and chlorine demand and decay (CDD) during disinfection with free chlorine and chloramines. This chapter summarizes the results of the October 2019 SDS evaluation. Detailed results from this October 2019 SDS evaluation are presented in a technical memorandum by PWB in Appendix C.

This testing evaluation was proposed as a trial run ahead of four quarterly SDS evaluations that will be completed around the same time PWB collects Stage 2 Disinfectants and Disinfection Byproducts Rule (D/DBPR) compliance samples. Historically, organic matter in the Bull Run water supply and DBPs formed during disinfection and distribution have been at the highest levels in the fall compared to any other time of the year.

When the pilot plant was sampled for the October SDS evaluation, each train was operated in conventional treatment mode with PACl dosed at 3.5 mg/L and nonionic filter aid polymer dosed at 0.010 mg/L. Train 1 was pre-chlorinated with a dose of 0.3 mg/L-Cl₂ and 13 minutes of contact time, and Train 2 was pre-ozonated with a dose of 1.0 mg/L-O₃ and 13 minutes of contact time. The raw water turbidity was 0.5 NTU, TOC was 1.4 mg/L, and the temperature was 12°C.

The objectives of the October SDS evaluation were to evaluate the following on the resulting disinfectant demand and decay and DBP formation after disinfectant dosing:

- Pre-oxidation using ozone dosed at 1 mg/L (Train 2) vs. chlorine dosed at 0.3 mg/L (Train 1)
- Filtration using GAC media vs. anthracite media
- Raw, unfiltered water vs. water treated using the combination of pre-oxidation, coagulation, flocculation, sedimentation, and filtration

Tests were carried out on samples collected from eight locations, including the pilot raw inlet, all six filter effluents, and PWB's Lusted Outlet distribution system entry point. Pilot raw inlet and filter effluent samples were treated with disinfection and corrosion control chemicals using doses that mimic conservative future treatment targets and compared with PWB's Lusted Outlet entry point water over a 14-day period. Treatment doses and conditions used during the October SDS tests are shown in Table 6-1. Treatment of pilot raw and filtered samples included sodium hypochlorite dosing to target a free chlorine residual of 2.5 mg/L after 60 minutes of contact time, followed by the addition of ammonium chloride, sodium bicarbonate, and sodium carbonate to convert free chlorine to monochloramine, and adjust pH and alkalinity to 9.0 and 30 mg/L-CaCO₃, respectively. The Lusted Outlet sample is fully treated PWB water collected at the distribution system entry point. At the time of testing, the Lusted Outlet sample had been treated at Headworks with 3.7 mg/L-Cl₂ (gaseous chlorine), and after 320 minutes of free chlorine contact time in the conduits, free chlorine residual was 2.5 mg/L before

dosing at Lusted Hill Treatment Facility with aqueous ammonia to form chloramines, and the addition of sodium hydroxide to target PWB's finished water pH of 8.2.

Table 6-1 Post-Filtration Treatment Targets used in October SDS Testing

Post-Treatment Element	Lusted Outlet (PWB Entry Point)	Pilot Samples (raw water and filter effluent)	Notes
Free Chlorine Contact Time	Contact time in Conduit 3 was 320 minutes on day of October SDS Testing	60 minutes	PWB is currently required to provide 3.0-log <i>Giardia</i> inactivation via free chlorine contact (30 to 90 minutes contact time depending on temperature and chlorine dose). A conventional plant would be required to provide 0.5-log inactivation following filtration (6 to 30 minutes contact time depending on temperature and chlorine dose). 60 minutes was selected as a conservative target.
Free Chlorine Residual Target (at end of Contact Time)	2.5 mg/L	2.5 mg/L	PWB Jan-June target is 2.2 mg/L and July-Dec target is 2.5 mg/L. 2.5 mg/L is used as a conservative target as, if anything, it may be desired to reduce the chlorine target once filtration is operational.
Secondary Disinfectant	Chloramines (ammonia dosed at Cl ₂ :NH ₃ -N ratio of 4.9:1)	Chloramines (ammonia dosed at Cl ₂ :NH ₃ -N ratio of 4.5:1)	Ammonia is added with corrosion treatment chemicals to convert free chlorine to monochloramine. For the purposes of pilot testing, it is assumed that chloramines will continue to be used for secondary disinfection.
Corrosion Control pH Alkalinity	Sodium Hydroxide pH = 8.2 No purposeful alkalinity adjustment	Sodium Bicarbonate, Sodium Carbonate pH = 9.0 Alk. = 30 mg/L- CaCO ₃	Current corrosion control pH target is 8.2. Proposed Improved Corrosion Control Treatment (ICCT) will increase pH and alkalinity to the ranges of 8.6-9.0 and 25-40 mg/L-CaCO ₃ at entry point to maintain a pH of 8.6 in the system.

Following treatment, all samples were stored in 1-L amber glass bottles with temperature maintained between 8°C and 15°C, a range similar to the October temperature in PWB's distribution system. Sampling for water quality analyses, including THMs and HAAs, was performed at the beginning, middle, and end of the 14-day SDS period. Results for 14-day DBP concentrations and CDD are summarized in Figure 6-1 and Figure 6-2, below.

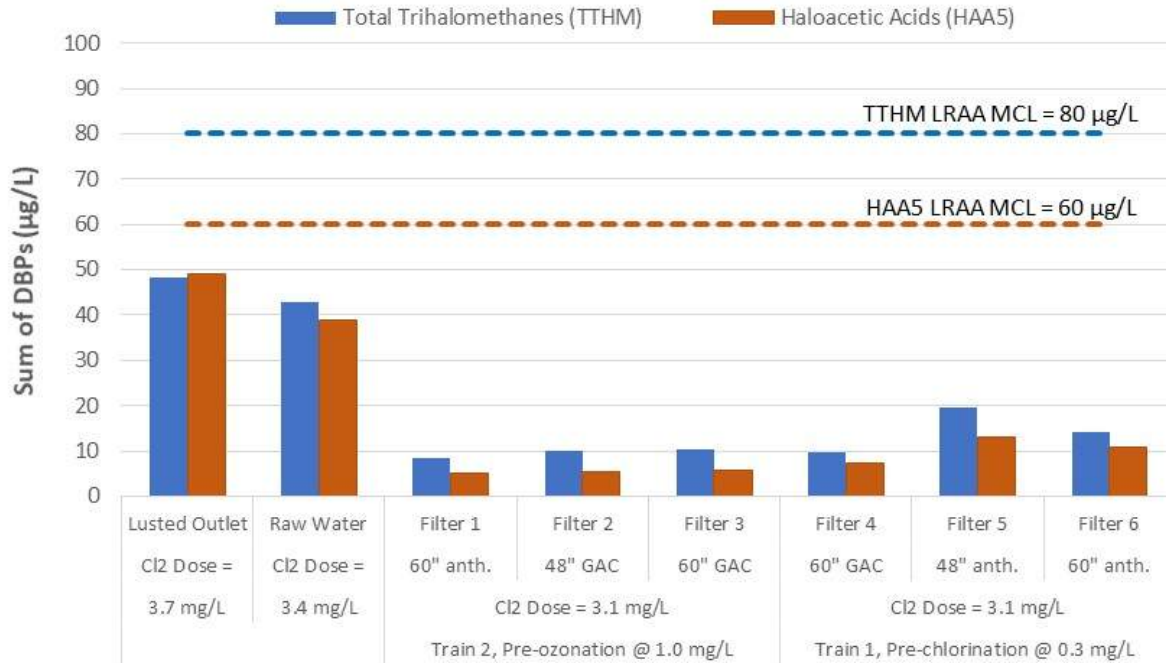


Figure 6-1. SDS test results for 14-day TTHMs and HAA5s

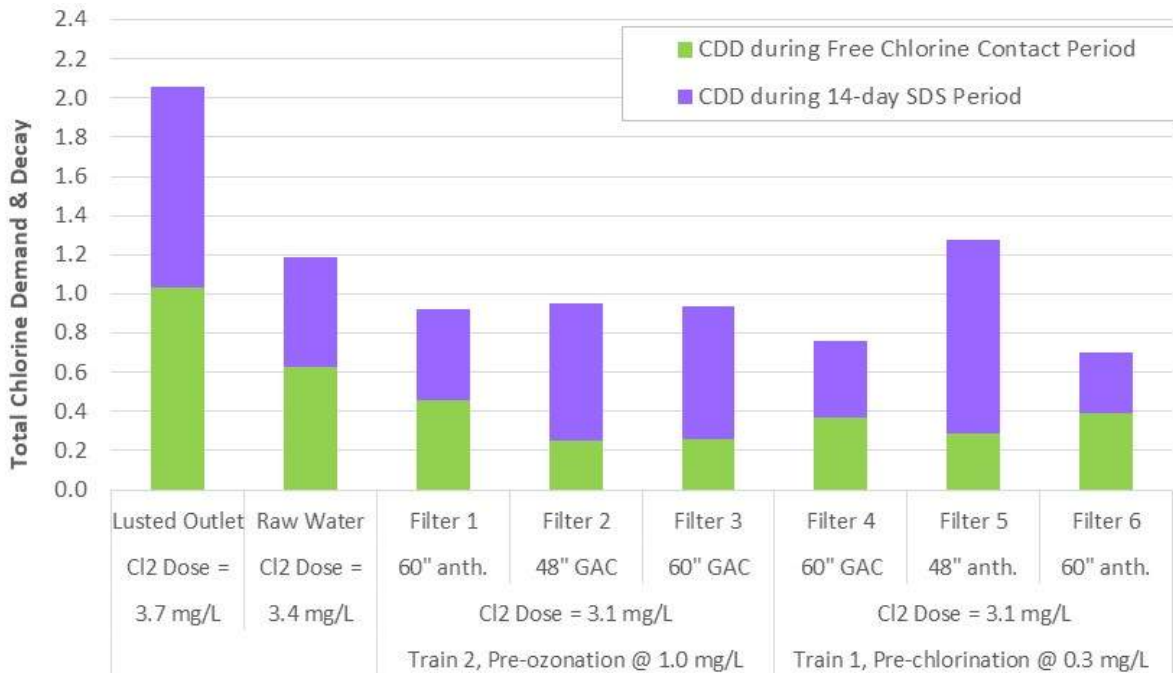


Figure 6-2. SDS test results for chlorine demand and decay

The following is a summary of key findings from the October SDS evaluation:

Comparison of Results for SDS Tests Conducted on Unfiltered Samples

- In the Lusted Outlet sample, chlorine dropped 1.1 mg/L during the free chlorine contact period and 1.0 mg/L during the subsequent 14-day SDS period, representing a combined CDD of 2.1 mg/L. Over the same timeframe, the chlorine in the pilot's raw water sample dropped 1.4 mg/L, a difference of 44 percent from the Lusted Outlet sample. The reduction in the chlorine demand is thought to be associated with the shorter free chlorine contact time (60 minutes vs. 320 minutes) as well as the higher pH target (9.0 vs. 8.2). While PWB does not have much flexibility in controlling the time water travels in the conduits and contacts with free chlorine, this result is meaningful as it indicates that chlorine could be more stable in the distribution system following implementation of ICCT in 2022.
- The 14-day HAA5 and TTHM results for the treated raw water sample were 22 percent lower and 11 percent lower, respectively, than levels in the Lusted Outlet sample. These reductions are associated with the lower chlorine dose, lower free chlorine contact time, and higher pH used for the pilot raw water sample.
- DBP concentrations in unfiltered samples increased significantly over the 14-day SDS period. HAA5 concentrations increased 22 percent in the Lusted Outlet sample and 30 percent in the pilot raw water sample. TTHM concentrations increased 43 percent in the Lusted Outlet sample and 64 percent in the pilot raw water sample. This finding is consistent with what is observed in historical PWB DBP sampling and indicates, even though chloramines are used for secondary disinfection, that DBPs increase significantly during distribution.

Comparison of Filtered Samples with Lusted Outlet Sample

- The CDD over the combined free chlorine contact and 14-day chloraminated SDS period ranged between 0.75 mg/L and 1.4 mg/L in filtered SDS samples. Compared with the Lusted Outlet sample, this represents a decrease in CDD of 35-66 percent.
- DBPs in all filtered samples were reduced well below 50 percent of their respective MCLs. As shown in Figure 6-1, the 14-day DBP results for all filtered samples were all below 20 µg/L.
- Chlorine loss during the 14-day chloraminated SDS period was significantly affected by the chlorine-to-ammonia dosing ratio. For example, despite common pre-treatment and similar media (anthracite over sand), chlorine dropped 0.99 mg/L in the Filter 5 sample, and 0.31 mg/L in the Filter 6 sample during the 14-day chloraminated SDS period. The chlorine-to-ammonia dosing ratio was calculated to be 5.3 for Filter 5 and 4.4 for Filter 6.

Comparison of Filtered Samples Treated with and without Ozone

- CDD, inclusive of pre-chlorine, measured in samples from ozonated Filters 1 and 3 was higher than in their pre-chlorinated counterparts (Filters 4 and 6). This result suggests that the ozonated train is producing higher levels of oxidizable material than the pre-chlorinated train. Additional investigation is needed to confirm this result and identify improvements that can be made.
- DBP concentrations were lower in samples collected from the pre-ozonated filters than in samples collected from the pre-chlorinated filters. HAAs measured after 14 days ranged between 5.0 and 5.8 µg/L in ozonated samples and 7.4, and 13.0 µg/L in pre-chlorinated samples. THMs measured after 14 days ranged between 8.5 and 10.4 µg/L in pre-ozonated samples, and 9.7 to 19.5 µg/L in pre-chlorinated samples.

Comparison of Samples Filtered with GAC vs. Anthracite

- Within Train 1 (pre-chlorine), the GAC-filtered sample (Filter 4) had the lowest DBP levels. Within Train 2 (pre-ozone), samples collected from the GAC filters (Filters 2 and 3) did not have lower levels of DBPs than the anthracite filter (Filter 1). While the GAC filters do consistently remove more TOC than the anthracite filters, their benefit for the reduction of DBPs and chlorine demand appears to be modest.

The results of the October 2019 SDS evaluation indicate that conventional treatment is highly effective for controlling the formation of regulated DBPs and reducing the loss of chlorine during disinfection and distribution of PWB's water. Future SDS tests will incorporate analysis of unregulated DBPs and Flavor Profile Analysis testing.

Chapter 7

Summary of Interim Pilot Plant Results

This Interim Pilot Study Report presents the results of the PWB Pilot Study from the first four months of operations. This operational period covered the summer season and the first month of the fall season (July–October 2019). Preliminary conclusions are presented based on the data available at this time and will be refined as the remainder of the study continues through 2020. Results were presented for the initial coagulation selection and testing, pre-oxidation testing with ozone and chlorine, and DF testing. During this period, SDS testing was also completed. Key findings are summarized below. These findings are based on operational targets to meet the PSW (filtrate turbidity of less than 0.1 NTU).

Summer Season Coagulation Selection and Testing:

Alum, ACH, ferric, and PACl were compared. Multiple coagulants were able to produce acceptable water quality and a more detailed comparison of alum and PACl was conducted. Testing revealed the following key conclusions:

- Ferric coagulation was difficult to find appropriate conditions to produce acceptable water quality during the coagulant comparison testing despite testing dosages ranging from 0.8 to 5.8 mg/L.
- Filter run times were shorter with ACH due to turbidity breakthrough, and removal was slightly less for TOC and color than PACl and alum.
- PACl and alum outperformed ferric and ACH and were selected for further testing. PACl tended to have higher UFRVs compared to performance with alum. Organics removal with PACl and filter aid was slightly improved compared to removal with alum. PACl also has less impact to pH and alkalinity on this low alkalinity source water when compared to alum. Based on the initial coagulant selection and testing, PACl was selected for continuous operation for the rest of the operational period.
- Filter aid improved treatment with both alum and PACl and was dosed with the selected coagulant, PACl, for further testing.
- Coagulant aid was not found to improve settled water or filtered water quality under the conditions tested, but will be further tested.
- In the low-turbidity Bull Run source water, all coagulants tested increased settled water turbidity above that of the raw water. This has not adversely impacted filtered water effluent quality.

Pre-oxidation Testing:

Pre-oxidation with ozone was compared to no oxidation from August 30–September 29. Testing revealed the following key conclusions:

- Ozone significantly improved filtration performance vs. no oxidization. On average, the 50th percentile UFRVs with pre-ozonation were 1.5 times greater than the filters with no pre-oxidant. The UFRVs on both trains exceeded the goal of 6,500 gal/sf-run during 95 percent of the operational time. All of the filters' 50th percentiles were at or greater than 10,000 gal/sf-run.

- Particle counts were higher with pre-ozonation compared to no pre-oxidant. However, all but one filter met the goal of having less than 50 particles/mL in the 5 to 15 μm range (95 percent of the time). The pre-ozonated anthracite filter at 12 gpm/sf (Filter 1) was just slightly above that goal with a 95th percentile value of 56 particles/mL.
- Pre-ozonation improved UV₂₅₄ removal (an average of 92 percent in the ozonated train compared to 78 percent in the train with no pre-oxidant). Both trains showed good color removal (greater than 50 percent) and TOC removal (approximately 50 percent).

Pre-ozonation and pre-chlorination were compared in October at dosages of 1.0 mg/L and 0.3 mg/L, respectively. Filter productivity was adjusting to a shift in raw water quality during the entire testing period, so only a week of data were used for the analysis. The limited testing illustrated the following:

- Chlorine and ozone use resulted in comparable UFRV. All of the filters exceeded the water production goal for a UFRV in excess of 6,500 gal/sf-run, 95 percent of the time. In almost all cases, the median value of the UFRVs exceed 10,000 gal/sf-run (except for the pre-chlorinated GAC filter operating at 12 gpm/sf).
- Pre-chlorination tended to have fewer particles in the filtered water than pre-ozonation, but testing will continue when pre-treatment is better adjusted for raw water conditions.
- Despite the expected seasonal increase in raw water TOC from approximately 0.75 mg/L in September to over 1 mg/L in October, both trains did a good job in terms of organics removal through the testing period. Pre-ozonation performed slightly better, showing 90 percent removal of UV₂₅₄ compared to 82 percent removal for the pre-chlorinated train. Both trains removed a similar amount of TOC (approximately 50 percent).
- The pre-ozonation train performed consistently during this test period (comparing pre-ozone to pre-chlorine) as to the previous test period (comparing pre-ozone to no pre-oxidant). It removed a similar amount of TOC and UV₂₅₄. Greater than 70 percent color removal was observed during this limited test period.

Additional pre-ozonation and pre-chlorination testing will be conducted to see if these findings are replicated with other oxidant doses and during other seasonal conditions.

Direct Filtration:

An initial trial for DF (e.g., no sedimentation) was tested for two weeks compared to conventional treatment with the same chemical dosages for both trains. Operational conditions that met PSW criteria were not found for DF to operate effectively. During this initial trial, chemical dosing was not optimized for DF. Additional testing would be needed to understand operation of DF.

Overall Filter Performance:

Filter performance was evaluated for differing filtration rate and filter media over the entire test regime. There were many different operational conditions over the entire test regime, so this section draws some general conclusions.

- **Filtration Rate:**
 - All of the filters had low levels of filtrate turbidity. All of the 6 filters met the water quality goal in the summer and fall seasons to have the 95th percentile turbidity in the individual filter effluent be less than 0.1 NTU.
 - The 8 and 12 gpm/sf GAC filters had similar performance. The 8 gpm/sf anthracite filter had a slightly better performance than the 12 gpm/sf anthracite filter on Train 1.

- UFRVs from acceptable filter runs for the first four months of operations were compared at the different filtration rates to understand if there was a difference in performance based on filtration rate. On average, the filters operating at 8 gpm/sf had higher UFRVs than the filters operating at 12 gpm/sf. All of the filters' median UFRV exceeded the goal of 10,000 gal/sf-run. Except for filter 1, all of the filters' minimum value of the representative filter runs was above the UFRV goal of 6,500 gal/sf-run.
- Organics removal was comparable at both filtration rates; low (6 and 8 gpm/sf) and high (8 and 12 gpm/sf), revealing that higher filtration rates did not result in worse organic removal performance.
- **Filter Media:**
 - All of the filters had low levels of filtrate turbidity.
 - Anthracite media filters had higher UFRVs than GAC filters at a filter loading rate of 12 gpm/sf. This is because GAC filters had higher CBHL. The GAC filters were paired with a smaller diameter sand. CBHL also increased over the operational time period. The increase in CBHL in the GAC filters is also likely due to increased biological activity in the filters. Higher CBHL leads to reaching terminal head loss faster and limits the filter run time.
 - GAC media consistently removed more TOC than anthracite filters, with or without pretreatment with a pre-oxidant. This may be attributable to the fact that virgin GAC was used for the filters, so the adsorptive capacity of the GAC for TOC was not exhausted for much of the time frame included in this report. The differential in TOC removal between the anthracite and GAC filters decreased over the duration of the test period, suggesting that the adsorptive capacity of the GAC may have begun to diminish as available adsorption sites were occupied.
 - In general, GAC media removed UV₂₅₄ more effectively than anthracite media. There was a smaller difference in UV₂₅₄ removal between the media types when an oxidant was added, given that there was additional UV₂₅₄ reduction in both filter types with pre-oxidation.
 - Given the fact that filtration performance (at 12 gpm/sf) was better in the anthracite filters and the anthracite filters had good organics removal (averaged between 40 to 50 percent), it is recommended that the GAC media be swapped with additional anthracite media to allow for more scrutiny of the effective size, media depth, and filter loading rates.
- **Chlorine Demand/Decay and DBPs:**
 - CDD decreased significantly with conventional treatment when compared to Lusted Outlet samples and DBPs were reduced below the 50% of their respective MCL goal
 - DBP concentrations were lower in pre-ozonated samples when compared to pre-chlorinated samples and when pre-ozonated, media type did not significantly affect the DBPs.

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Appendix A: Jar Testing Report(s)



Technical Memorandum

Subject: Bull Run Water Jar Testing Procedure

PWB Project: 30006570

BC Project: 152606

Date: January 25, 2019

To: Yone Akagi, Water Quality Manager

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CONTENTS

1. Approach and Theory.....	1
1.1 Approach.....	1
1.2 Theory.....	1
2. Experimental Design.....	2
2.1 Jar Testing Equipment.....	2
2.2 Raw Water Sampling and Preparation.....	3
2.2.1 Process Water.....	3
2.2.2 Turbidity Spiking.....	4
2.3 Jar Testing Conditions and Sampling.....	4
2.3.1 Mixing Conditions and Chemical Selection.....	4
2.3.2 Phased Chemical Dose Testing.....	6
2.3.3 Recording Test Results.....	8
2.3.4 Filterability Index Test.....	8
2.3.5 Simulated Distribution System and/or DBP Formation Potential.....	9
References.....	10
Attachment A: Phipps & Bird Velocity Gradients (sec^{-1}).....	A-1
Attachment B: Jar Testing Sample Data Sheet.....	B-1
Attachment C: Chemical Dosing Calculations.....	C-1

List of Figures

Figure 1. Jar testing apparatus.....	2
Figure 2. Filterability testing equipment.....	3

List of Tables

Table 1. Mixing conditions for each test.....	5
Table 2. Summary of chemicals to be used during jar testing.....	5
Table 3. Phase 1 pre-screening jar test experimental matrix.....	6
Table 4. Phase 2 optimized jar test experimental matrix.....	7
Table 5. Phase 3 optimized jar test experimental matrix with cationic polymer (CP).....	7
Table 6. Phase 4 jar test experimental matrix with anionic or nonionic polymer (AP or NP).....	8

List of Abbreviations

ACH	aluminum chlorohydrate
AP	anionic polymer
BC	Brown and Caldwell
BRFP	Bull Run Filtration Project
CaCO ₃	calcium carbonate
Confluence	Confluence Engineering Group LLC
°C	degrees centigrade
CP	cationic polymer
DBP-SDS	disinfection by-product
DI	deionization
DOC	dissolved organic carbon
FI	filterability index
FP	formation potential
gpd	gallons per day
gph	gallons per hours
IP	ionic polymer
L	liter
lf	linear feet
mgd	million gallons per day
mg/L	milligrams per liter
NaHCO ₃	sodium bicarbonate
μm	micrometer
PACl	polyaluminum chloride
PWB	Portland Water Bureau
SDS	simulated distribution system
TBD	to be determined
TOC	total organic carbon
TM	technical memorandum
WTP	water treatment plant

1. APPROACH AND THEORY

This Technical Memorandum (TM) presents jar testing methods for the Portland Water Bureau (PWB) to evaluate NSF rated coagulants and coagulant aids in order to select chemicals for use during pilot-scale testing.

It should be noted that this approach is a recommendation for the methods that should be used for jar testing, but (as usually may occur during jar testing), procedures and conditions such as actual chemical dosages may be adjusted after jar testing experience is gained. Adjustments to test plan recommendations and conditions in order to optimize this work should be discussed on a regular basis with the project team as testing is completed.

1.1 Approach

The approach is based upon conducting a multi-phased group of jar test runs. This process will evaluate coagulation performance with Bull Run water across four phases of tests by (1) performing a wide-range dose screening of coagulants, (2) evaluating optimized coagulant dosages with pH adjustment, (3) evaluating coagulation assisted by cationic polymer(s), and (4) evaluating coagulation assisted by nonionic and/or anionic polymer(s). Frequency of conducting this jar testing will be determined later by the project team.

Jar tests may later be combined with testing for other water quality issues such as disinfection by-product simulated distribution system (DBP-SDS) or other issues. Those additional testing procedures will be developed as needed and appended to this instruction.

1.2 Theory

The primary purpose of jar testing is to rapidly evaluate coagulants and/or coagulant and polymer combinations for their ability to remove particulate, color, and organic matter from the Bull Run supply. Coagulation destabilizes colloidal particles that would not normally settle naturally, such that the colloids can be flocculated into small particles capable of being settled and/or filtered from solution. A subsequent confirmation of jar test findings will be completed at the pilot treatment facility to characterize treatability in combination with granular media filtration.

Jar testing will be conducted mainly with inorganic, metal-salt coagulants anticipated to include:

- Hydrated aluminum sulfate (i.e., alum as 49% $\text{Al}_2[\text{SO}_4]_3 \cdot 14\text{H}_2\text{O}$ solution), 17% active Al_2O_3 ;
- Ferric chloride (35% $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ solution), 35% active Fe (twice the reactive metal salt as alum); and,
- Polymeric aluminum coagulants such as polyaluminum chloride (PACl) or aluminum chlorohydrate (ACH) which may come in various chemical constituencies.

Both alum and ferric chloride consume alkalinity when added to water. In contrast, PACl and ACH are partially pre-hydrolyzed and therefore consume significantly less alkalinity. To compensate for this, jar testing will include boosting raw water alkalinity. Note that several of these coagulants may also perform better at different pH ranges. For example, polymeric aluminum coagulants may react quicker, perform better in colder waters, and operate over a wider pH range, but they may be more expensive and are based on proprietary manufacturer formulations. Once the approximate dose range is identified in Phase 1, optimization of coagulation pH will be included during Phase 2 testing.

The addition of a cationic polymer is conducted to assess the benefit of adding a long-chain polymer that may group/entrap destabilized colloids and form larger floc structures. The grouping of larger floc may allow for more rapid settling and/or removal through filtration. It is also possible that cationic polymers may be used as the only coagulant (i.e., without metal-salt coagulants) with and without nonionic or anionic polymers. Cationic-polymer alone conditions will be evaluated in Phase 1 tests. Evaluating the use of filter-aid polymers will be deferred for subsequent pilot-testing.

Nonionic, anionic and even weakly cationic organic polymers are used typically as flocculant and/or coagulant aids rather than as primary coagulants. These chemicals do not impact particle charge, but are used solely to improve floc formation. These polymers are typically of a much greater molecular weight when compared to cationic polymers and can form larger floc. Testing of the performance of such polymers in a direct-filtration mode when more rapid floc formation and removal is required may be beneficial prior to conducting pilot-scale testing.

2. EXPERIMENTAL DESIGN

The approach used in this test design is to conduct a 4-phased run of jar tests. Testing includes the following water collection and jar test run conditions:

- Conduct jar tests on water collected at different times (e.g., from at least Nov/Dec 2018 and Mar/Apr 2019) prior to the start of pilot testing in Apr/May 2019;
- Complete coagulant dose pre-screening (Phase 1) with a wide range of dosages;
- Complete a finer screening at optimal pH (Phase 2) with optimal performing dosages from Phase 1;
- Complete Phase 3 by evaluating optimal dosages from Phase 2 with cationic polymer(s); and,
- Complete Phase 4 by evaluating optimal dosages from Phase 2 with nonionic or anionic polymer(s).

2.1 Jar Testing Equipment

The jar testing apparatus to be used for these experiments is a 6-jar, programmable gang-stirrer apparatus with square, 2-liter (L) jars illustrated in **Figure 1**. Mixing using the attached stirrers operates at an equivalent speed across each jar depending on the control panel setting. Stirrers are engaged during coagulation and flocculation conditions while turning off the stirrer simulates quiescent settling (sedimentation). Chemical addition is accomplished by adding chemicals at the top of each jar at the onset of a test. Sampling is conducted by withdrawal at a slow rate through sample ports (e.g., a low flow rate that does not disturb floc blankets located below the sample port) at the bottom of each jar.



Figure 1. Jar testing apparatus

Apparatus operating instructions are not included in this testing plan.

To simulate treated water filterability following jar testing, equipment illustrated in **Figure 2** is recommended based upon industry guidance (Kawamura 2000). The goal of the filterability test can be to measure (a) water quality after passing through the filter, and/or (b) the amount of time it takes for the water sample to pass through the filter. The setup for filterability tests involves folding an 11-micrometer (μm) pore size filter paper in half twice (to achieve a triangular shape), inserting the folded filter paper into the funnel and expanding it to match the funnel shape, and then inserting the funnel into the flask. Test water will then be poured through the filter-equipped funnel based on instructions provided below. An alternative to this equipment is to use a vacuum filter apparatus without applying a vacuum (i.e., a beaker that is topped with a magnetically-attached reservoir, with filter paper held between the two). This alternative will be discussed with the project team to determine the method desired for implementation.



Figure 2. Filterability testing equipment

Equipment includes filter paper (left), and funnel and flask (center), with setup shown at the right.

2.2 Raw Water Sampling and Preparation

Raw, untreated (i.e., without addition of chlorine or any other chemicals) water from the Bull Run watershed will be collected and stored in a laboratory refrigerator (i.e., <10 degrees centigrade [$^{\circ}\text{C}$]). Once collected and stored, the water should be tested within 3 months of sample collection. Water should be collected in clean, rinsed (using sample water), 10-L, low-density polyethylene (or similar inert plastic material) cubitainers. At least 200-L of water (i.e., 20, 10-L cubitainers) should be collected for each, 4-phase jar testing event, for each sampling period. It is recommended that sample collection time and turbidity value be recorded during collection of the water sample from each 10-L cubitainer.

Water is proposed to be collected for jar testing during the following time periods:

1. November 2018 – This is anticipated to be the time during which the Bull Run water has its greatest DBP-SDS and (possibly) increased levels of organic matter.
2. January and/or February 2019 – This may be the time of spring runoff, when turbidity in the Bull Run may increase.
3. April 2019 – This might be the last time period available for jar testing alone prior to the start-up of pilot testing. Jar testing may continue in parallel with pilot testing, to be determined by the project team.

2.2.1 Process Water

Process water (except for negative control samples) requires alkalinity adjustment in order to compensate for consumption from coagulants. Immediately prior to the start of the rapid mixing step, reagent grade sodium bicarbonate (as NaHCO_3) should be added. Procedures for preparing a stock solution of NaHCO_3 are provided in **Attachment C**. The recommended stock solution will allow for alkalinity to be increased by approximately 24 mg/L alkalinity as calcium carbonate [CaCO_3]]. This will

allow enough alkalinity to support coagulant reactions for up to 40 mg/L of alum or up to 25 mg/L of ferric chloride without consuming the background level of alkalinity in Bull Run water (e.g., raw water alkalinity is expected to range from 5 to 12 mg/L as CaCO_3).

The procedure for dosing alkalinity, as per **Attachment C**, should be as follows: fill each of the beakers with 1,990 mL of Bull Run water and add 10 mL of 0.8% stock NaHCO_3 solution. This will allow the jars to be filled to 2-L with an added 24 mg/L alkalinity. Note that the amount of NaHCO_3 added may need to be increased when performing jar tests on water with turbidity spiking (because coagulant dose may need to be increased). This increase will be determined by the project team.

2.2.2 Turbidity Spiking

A future amendment to this jar testing plan may include work evaluating coagulant effectiveness during elevated turbidity events. To prepare for this future work, it may be advantageous for PWB to collect one of the following (exact volume to be determined at a later time):

- A smaller volume (possibly only 50 L) of high-turbidity water (i.e., >25 NTU) from a tributary that might be used as a spiking solution for jar tests, or
- A standard volume (200 L, per text above in **Section 2.2**) of moderate turbidity water (i.e., turbidity between approximately 1 and 25 NTU).

This water will be collected using the same procedures above, and stored under similar conditions. Samplers should also measure water temperature when collected so that the difference between actual and jar test conditions can be noted. Following collection, test conditions will need to be confirmed. Instruction for testing to be conducted with these turbid water samples will be included in a later amendment to this document.

2.3 Jar Testing Conditions and Sampling

Jar testing is to be conducted on raw, untreated (i.e., without addition of chlorine) Bull Run water. The conditions described below summarize mixing settings and chemical addition protocols to be followed.

2.3.1 Mixing Conditions and Chemical Selection

Mixing conditions for all jar tests are outlined in **Table 1**. Each round of testing calls for 6 jars to be filled with a 2-L volume comprised of test water and NaHCO_3 stock solution (per **Section 2.2.1** above), resulting in using a total of 12-L of alkalinity-adjusted, raw water. Mixing is tapered across three conditions that include rapid mixing, three-stage flocculation, and settling. Rapid mixing includes the most intense mixing across a duration of 30 seconds with coagulant added immediately after mixing is initiated and alkalinity is adjusted.

For ease of dosing, it is recommended that chemicals are added with dosing syringes (see dosing procedure in **Attachment C**). Flocculation includes 3-stage, tapered (decreasing) mixing, with each stage lasting 10 minutes. Settling (no mixing) will last up to 60 minutes. Although this approach does not evaluate direct-filtration operations, it is expected to provide an effective relative evaluation of coagulant and polymer performance. Extensive direct filtration assessments may be completed later during pilot-scale testing, they also can be evaluated here by collecting a sample of water to analyze and/or complete a filterability evaluation immediately after flocculation and prior to starting the settling phase. This direct-filtration option should be considered by the project team and implemented as needed.

Table 1. Mixing conditions for each test

Parameter	Rapid Mixing ^b	Flocculation ^c			Settling
		Stage 1	Stage 2	Stage 3	
Mixing speed (rpm)	300	60	35	20	0
Time, t (min)	0.5	10	10	10	30/45/60 ^d
Mixing energy, G (sec ⁻¹) ^a	380	54	26	14	0
G x t	--	3.2 x 10 ⁴	1.6 x 10 ⁴	8.4 x 10 ³	0

a. G values calculated based on 2-L, square jars at 22 °C using a Phipps and Bird® stirrer, model PB-900 (see **Attachment A**).

b. Coagulants should be added after both the addition of alkalinity solution and after paddles are started for rapid mixing.

c. Polymers (cationic, nonionic, anionic) to be added at the end of rapid mixing and the start of flocculation stage 1.

d. Water quality can be analyzed after 30, 45, and 60 min of settling in the first several jar tests to determine when steady-state conditions are achieved. In the absence of data at 30 and 45 min, tests should default to 60 min.

A summary of chemicals to be used in jar testing is provided in **Table 2**.

Table 2. Summary of chemicals to be used during jar testing

Trade Name	Chemical Description	Purpose	Expected Dose Range*
Sodium bicarbonate	NaHCO ₃	Alkalinity addition	40 mg/L (24 mg/L as CaCO ₃)
Alum	Al ₂ (SO ₄) ₃ •14H ₂ O 49% solution (TBD)	Coagulant	Up to 15 mg/L of active strength chemical
Ferric chloride (PIX-311)	FeCl ₃ •6H ₂ O 35% solution (TBD)	Coagulant	Up to 10 mg/L of active strength chemical
PACL (PAX-18)	Al ₂ O ₃ 8-24% solution	Coagulant	Up to 15 mg/L of active strength chemical
ACH (PAX-XL19)	Al ₂ (OH) ₅ Cl 10-30% solution	Coagulant	Up to 15 mg/L of active strength chemical
Cationic Polymer ^e (Clarifloc C-3226)	Proprietary	Flocculant aid	Up to 8 mg/L
Cationic Polymer ^e (Praestol 851TR)	Proprietary	Flocculant aid	Up to 8 mg/L
Cationic Polymer ^e (Praestol 650TR)	Proprietary	Flocculant aid	Up to 8 mg/L
Anionic Polymer ^e (Praestol 3040 LTR)	Proprietary	Flocculant aid	Up to 5 mg/L
Nonionic Polymer ^e (Praestol 2500)	Proprietary	Flocculant aid	Up to 5 mg/L
Acid (sulfuric acid) ^f	Sulfuric acid* as H ₂ SO ₄	pH adjustment	As needed
Base (sodium hydroxide) ^f	Sodium hydroxide* as NaOH	pH adjustment	As needed

* Dose range is based upon low-turbidity raw water. Range may be increased if spiking or elevated turbidity water is tested.

e. Cationic, anionic, and nonionic polymers will be dosed as neat chemical (not based on chemical formula).

f. Acid and base chemicals are recommended to be sulfuric acid and sodium hydroxide for Phase 2, 3, and 4 tests, but will be determined later by the project team depending on availability & PWB preference.

2.3.2 Phased Chemical Dose Testing

Jar testing will be completed in a phased approach as described in **Tables 3 through 6**, below. Each phase should be expected to require nearly one full day of effort for the jar test technician to complete due to water and jar testing preparation, actual jar testing that includes up to one hour of settling per condition with settling rate recorded (see settling rate note at bottom of **Attachment B**), subsequent filterability index (FI) testing and water quality analyses to be completed by the technician, and repeating the test across the four separate conditions. Note that chemical dose calculations (how much chemical to add) and addition methods (when/how to add chemical) are included in **Attachment C**.

A general approach for one week of jar testing will be as follows, described in further detail below:

1. Prepare chemical stock solutions from neat/original chemicals.
2. Remove water from refrigerated storage 24 hours prior to tests (reach room temperature).
3. Run analytical samples for the week on the raw water prior to jar testing, consisting of pH, turbidity, UV₂₅₄, apparent color, alkalinity, TOC, and DOC.
4. Conduct Phase 1 tests (measure raw water temperature prior to starting each test).
5. Place water in jars, adjust alkalinity, and prepare chemical dosing syringes before each test.
6. Run test and collect/analyze settling rate and turbidity at 30 and 45 minutes.
7. Collect 60-minute settled water samples, analyze, and run the FI tests and associated sampling.
8. For Phases 2, 3, and 4, repeat above 4 through 7, but conduct #5 twice: first, perform a pre-test to determine acid/base needs to adjust pH to 6.5 units (see instruction in **Attachment C**) at each coagulant dose; second, perform jar test with acid or base added during coagulation.

For Phase 1 (**Table 3**), jar test results will be compared to raw water quality (see #3 above) and theoretically produce U-shaped removal curves according to the dose conditions used. For example, Phase 1 Condition 1a alum tests ranging from 0 to 15 mg/L may result in the 0 and 15 mg/L dosages being inefficient (i.e., elevated solids/organics remain in settled water supernatant) while one or two mid-range dosages produces optimal reduction of solids/organics. This is the referenced “U-shape” for test results. The best performing doses (showing optimal solids/organics removal and forming the bottom of the U shape data curve) will be further evaluated during Phase 2.

Table 3. Phase 1 pre-screening jar test experimental matrix			
Condition ^g	Chemical	Dosages ^h	Settled Water Analyses
1a	Alum	0, 1, 3, 6, 10, 15	Jar test technician samples: Visual floc appearance; settling velocity; temperature; pH; Turbidity; UV ₂₅₄ ; apparent color; FI ^j
1b	Ferric chloride	0, 1, 2, 5, 8, 10	
1c	PACl ⁱ	0, 1, 3, 6, 10, 15	
1d	ACH ⁱ	0, 1, 3, 6, 10, 15	Laboratory samples: Alkalinity; TOC; DOC
1d	Cationic Polymer	0, 0.5, 1, 2, 4, 8	

FI = Filterability index.

g. Each condition includes testing 6 jars with water previously dosed with 40 mg/L (24 mg/L as CaCO₃) sodium bicarbonate.

h. Dosages should be calculated based upon active chemical in the coagulant (e.g., Alum dose = mg/L as Al₂(SO₄)₃•14H₂O) and may need to be increased if turbidity spiking / elevated turbidity tests are conducted.

i. Percentage active chemical needs to be determined so it can be used in the dosing calculation (see **Attachment C**)

j. See text below describing water analyses required during FI testing.

Phase 2 testing (**Table 4**) should be conducted by identifying a range of coagulant dosages that fall between the best/optimal performing dosages observed during Phase 1 and then adjusting pH conditions to allow equivalent conditions to be evaluated. For example, if the best performing alum dosages in Phase 1 were 1 and 3 mg/L, then Phase 2 alum test dosages may become 0.5, 1, 2, 3, and 4 mg/L. Phase 2 dose selection can only be selected after completing Phase 1 and analyzing data (at least turbidity, apparent color, and Filterability Index [FI] results). After dosages are selected, it is recommended that pH be adjusted in each test jar (except the 0 mg/L control) to be 6.5 units. Details on performing pH adjustment are provided in **Attachment C**.

Table 4. Phase 2 optimized jar test experimental matrix			
Condition ^k	Chemical	Dosages ^k	Settled Water Analyses
2a	1 ^k	0, and 5 ^l doses	Jar test technician samples: Visual floc appearance; settling velocity; pH; temperature; turbidity; UV254; apparent color; FI ^k Laboratory samples: Alkalinity; TOC; DOC
2b	2 ^k	0, and 5 ^l doses	
2c	3 ^k	0, and 5 ^l doses	

FI = Filterability index.

k. Three chemicals at most will be chosen based on results from Phase 1; test conditions, coagulant dose calculation, percent active chemical determination, and FI testing to be similar to Phase 1.

l. Five doses that represent optimal conditions found in Phase 1 results, all adjusted to coagulation pH of 6.5 units.

Phase 3 (**Table 5**) tests will evaluate the effect of adding a cationic polymer (during flocculation) following the best performing coagulant dosages for each of the Phase 2 conditions. Each jar (excluding the 0 mg/L control jar) will have the exact same dose of coagulant (i.e., the best/optimal performing dose condition from Phase 2 should be selected) and cationic polymer dosages will range from 0 to 3 mg/L in the five jars. Cationic polymer should be added during the final seconds of the rapid mix stage (the last 5 to 10 seconds).

Table 5. Phase 3 optimized jar test experimental matrix with cationic polymer (CP)			
Condition ^m	Chemical	Dosages ^m	Settled Water Analyses
3a	1 ^m	0, coagulant ⁿ w/o CP, and coagulant w/CP ^o at 0.5, 1, 2, and 3 mg/L	Jar test technician samples: Visual floc appearance; settling velocity; pH; temperature; turbidity; UV254; apparent color; FI ^m Laboratory samples: Alkalinity; TOC; DOC
3b	2 ^m	0, coagulant ⁿ w/o CP, and coagulant w/CP ^o at 0.5, 1, 2, and 3 mg/L	
3c	3 ^m	0, coagulant ⁿ w/o CP, and coagulant w/CP ^o at 0.5, 1, 2, and 3 mg/L	

FI = Filterability index.

m. Three chemicals at most will be chosen based on results from Phase 1; test conditions, coagulant dose calculation, percent active chemical determination, and FI testing to be similar to Phase 1.

n. Choose the best performing (optimal) Phase 2 dose for each of the 5 test jars, and adjust pH to 6.5.

o. CP to be added neat (as chemical) to the 5 coagulant jars at the different dose rates as noted (if CP is one of the chemicals carried forward from Phase 2, do not add additional CP to the optimal CP dose).

Similar to Phase 3, the Phase 4 tests (**Table 6**) will evaluate the benefit of adding either an anionic or nonionic polymer to assist in settling (see **Attachment C** for instruction on how to add chemical to jars). Only one polymer should be used while completing a grouping of Phase 4 test conditions. Therefore, testing multiple polymers would require the entire Phase 4 matrix to be repeated (i.e., Phase 4i for an anionic polymer, Phase 4ii for a nonionic polymer, Phase 4iii for a second nonionic polymer, etc.). Phase 4 tests should use the same coagulant dose as in Phase 3.

Condition ^p	Chemical	Dosages ^p	Settled Water Analyses
4a	1 ^p	0, coagulant ^q w/o AP or NP ^r , and 4 jars with coagulant w/ AP or NP at TBD doses	Jar test technician samples: Visual floc appearance; settling velocity; pH; temperature; turbidity; UV254; apparent color; FI ^p
4b	2 ^p	0, coagulant ^q w/o AP or NP ^r , and 4 jars with coagulant w/ AP or NP at TBD doses	
4d	3 ^p	0, coagulant ^q w/o AP or NP ^r , and 4 jars with coagulant w/ AP or NP at TBD doses	Laboratory samples: Alkalinity; TOC; DOC

FI = Filterability index.

TBD = To be determined.

p. Three chemicals at most will be chosen based on results from Phase 1; test conditions, coagulant dose calculation, percent active chemical determination, and FI testing to be similar to Phase 1.

q. Use the same coagulant dose and pH condition as in Phase 3.

r. AP or NP to be added neat to the 5 jars at a dose rate TBD by the project team.

2.3.3 Recording Test Results

An example jar test data sheet is provided in **Attachment B**. Most of the test data to record can be entered into the datasheet, but additional information should also be collected, such as:

1. Results of FI testing;
2. Appearance of floc physical structure (photos are recommended following each stage of testing (e.g., rapid mix, each of the 3 flocculation stages, and settling); and,
3. Appearance of jars after settling is complete (video during settling is recommended).

2.3.4 Filterability Index Test

Filterability Index (FI) is a method used to quantify the filterability of a water sample when compared to a blank/control sample. The test will provide a comparative assessment of the filterability of the different settled waters; however, a more rapid filtering rate is not necessarily better. A rapid rate may be an indication of micro-sized particles passing through the filter membrane. The control sample that can be used for this jar testing would be raw, untreated water (from the control jar). The testing outlined here will only give comparative results, and therefore may only provide qualitative findings. Results from filterability tests will be used in combination with coagulation test results to make final decisions on which chemicals will be evaluated during pilot testing.

A traditional FI procedure would be to compare results to a control sample collected from a full-scale water treatment plant (WTP). However, because full-scale filtered water is not available in this situation, a modified FI procedure is recommended.

The following is a modified filterability index procedure recommended for PWB:

1. Collect 300 mL sample of settled water supernatant from each jar.
2. Measure turbidity of samples from each jar and record; use ≤ 100 mL of water.
3. Assemble the filter flask, cone, and filter paper as illustrated in Figure 2 and have a stopwatch ready for use.
4. Fully wet the filter paper with deionized (DI) water, discarding the used DI water.
5. Measure out 200-mL of remaining settled water sample.
6. Using the 200-mL sample, begin pouring it into the filter-lined funnel and immediately starting the stopwatch timer when water starts passing through the filter. Pour the entire 200 mL sample through the filter paper, paying attention to not overflowing the filter paper.
7. End the stopwatch timer when the last drops of water pass through the filter.
8. Measure turbidity of water that has passed through the filter.
9. Conduct the same test (above) with DI water alone. It is only necessary to conduct the DI test once per day for multiple jar tests. Also, do not use filter papers from different boxes (e.g., if there are only 2 filter papers left from one box, discard them and open a new box) as filter rates can be impacted significantly solely due to the different manufactured lots of filter paper.
10. Calculate the sample filtration time divided by the DI filtration time. This gives a dimensionless FI number for each sample.
11. Measure and record turbidity of water that has passed through the filter.

FI evaluation procedures include the following:

Optimum conditions – A low FI number and a low filtered water turbidity.

Filter breakthrough (poor performance) – A low FI number and a high filtered water turbidity.

Filter clogging (poor performance) – A high FI number and a low filtered water turbidity.

2.3.5 Simulated Distribution System and/or DBP Formation Potential

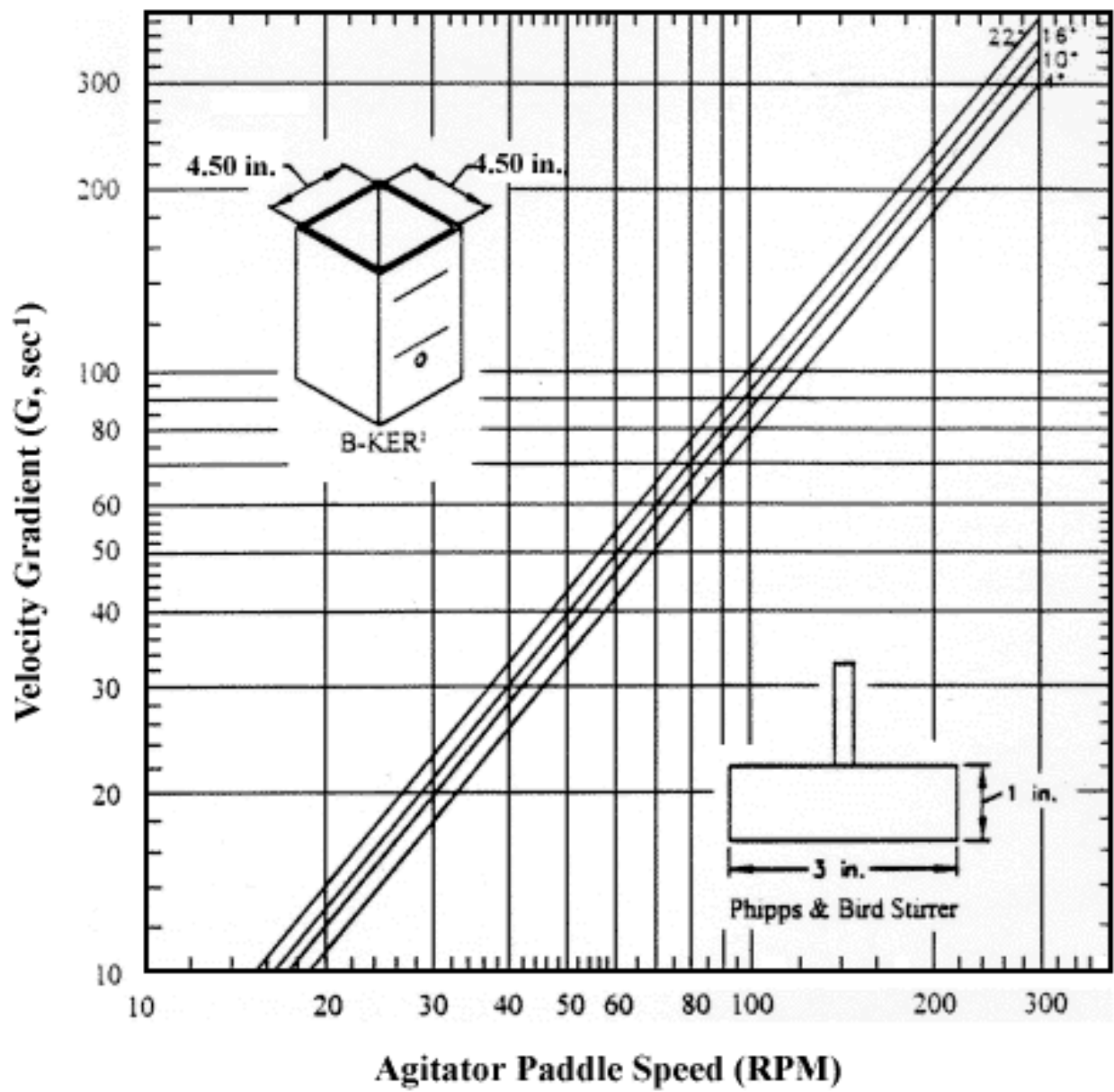
This plan does not include any sampling/testing for simulated distribution system (SDS) or disinfection by-product (DBP) formation potential (FP) testing. This may be added to this test plan in a subsequent document revision.

References

Kawamura, S., Integrated Design and Operation of Water Treatment Facilities, 2nd edition (2000).

Attachment A: Phipps & Bird Velocity Gradients (sec⁻¹)

From <https://www.phippsbird.com/pbinc/WaterWasteWater/Gcurve.aspx>



Attachment B: Jar Testing Sample Data Sheet

Portland Water Bureau Bull Run Water Jar Testing Results Form

Test ID: _____ Condition: _____

Technician(s) : _____ Date: _____ Test Description: _____

Operating Characteristics	Rapid Mixing	Floc 1	Floc 2	Floc 3	Settling	Chemical ID	Chemical Name	When Added	Notes
Time (min)						A			
Mixer Rate (rpm)						B			
						C			
						D			

Jar No.	Chemical ID (mg/L)				Floc Formation ¹		Settled Water Results at 30 / 45 / 60 minutes					Settle Rate ²	Notes
	A	B	C	D	Time (min)	Type	Turbidity (NTU)	Temp (°C)	pH (units)	App color (units)	UV ₂₅₄ (cm ⁻¹)	(at 30/45/60 min)	
	Raw water before alkalinity adjustment, any chemical addition, and any treatment (i.e., 'settled results' does not apply)												Raw water
1	0	0	0	0	---	---							Control jar
2													
3													
4													
5													
6													

Note: Prior to testing, add sodium bicarbonate to boost alkalinity, and mix well so that it is sufficiently dissolved.

¹ **Floc formation observed** = Time that it took (from the start of settling) for a floc blanket to form, along with a description of the floc within the blanket (e.g., haze, pin, small, moderate, large, weak, or strong)

² **Settling rate** = Distance of floc blanket settling (inches from initial formation to final rest) divided by the time that it takes for the blanket to settle (minutes). Mark floc level with pen on a piece of masking tape placed vertically on the jar before and at each measurement time. For example, if a floc formed a defined blanket that dropped 3.2 inches in 30 minutes = 3.2/30 = 0.11 in/min.

Attachment C: Chemical Dosing Calculations

Details for calculating amount of chemical added during jar tests

Alkalinity solution (using sodium bicarbonate)

Using reagent-grade sodium bicarbonate (as NaHCO_3) and DI water, create a stock solution to be added to raw water to boost alkalinity prior to testing. Prepare the stock solution for each water sampling from the Bull Run as follows:

1. Place a 1-L volume of raw Bull Run water in a beaker with stir bar; begin mixing on a stir plate with the heated plate set to warm.
2. After measuring out 8g of solid NaHCO_3 , add it slowly into the vortex of the mixing water with a spatula.
3. Allow warm solution to mix thoroughly so that it is fully dissolved, and then bring to room temperature prior to use. Label this as a 0.8% solution. Adding 10 mL of this stock solution provides a 40 mg/L dose into the 2-L jars. If additional alkalinity is needed in the jars due to greater coagulant dosages, more alkalinity can be added to the jars (e.g., each additional addition of 1 mL of stock to the 2-L jars provides 4 mg/L more alkalinity).
4. To start jar tests with an exact 2-L sample, add the 10 mL of NaHCO_3 stock solution into 1,990 mL of raw Bull Run Water. This can be done by filling jars with 2-L of test water and then removing 10 mL with a pipette before dosing 10 mL of stock solution). If additional alkalinity is needed, reduce the amount of Bull Run water accordingly so that the final volume of test water remains at 2-L.

For alum, ferric chloride, PACl or ACH:

From a neat/original solution, prepare a 1,000 mL volume of a stock/dosing solution each week (i.e., do not store more than 5 days) that you can use for multiple jar test experiments. The procedure below creates a 2 percent solution stock for dosing (it is important to keep the solution at 2 percent or more so that the product does not hydrolyze before being added to jars).

1. Create the dosing solution as follows:
 - a. For the neat solution (i.e., solution 1) and stock solution (i.e., solution 2), use the equivalency $C_1 V_1 = C_2 V_2$ where:
 - i. C_1 = (percent strength, g / 100 g) x (specific gravity, as g/mL)
 - ii. V_1 = Unknown amount to be used
 - iii. C_2 = (percent stock strength desired is 0.02; i.e., 2 g /100 g) x (specific gravity assumed as 1 g/mL) = 0.02 g/mL
 - iv. V_2 = 1000 mL
 - b. Example calculation using alum of 48% strength and 1.33 g/mL specific gravity
 - i. $C_1 V_1 = C_2 V_2$
 - ii. $(0.48 \times 1.33) \times V_1 = (0.02 \times 1) \times 1000 \text{ mL}$

- iii. $0.6384 V_1 = 200$
 - iv. $V_1 = 31.3$ mL of alum
 - v. Result: Create a 2% stock solution by adding 31.3 mL neat alum into 968.7 mL DI water. Adding 1 mL of this stock solution into a 2L jar results in a dose of 10 mg/L; adding 0.1 mL provides a dose of 1 mg/L; etc.
2. Use a dosing syringe to collect the volume of dosing solution to be added into a jar, and set the filled syringe next to the jar until it is ready to be added (e.g., collect 5 mL of dosing solution into a syringe if you want to create a 5 mg/L dose in the jar)
 3. Inject syringe contents into rapid mixing at time = 0.

For pH adjustment during Phase 2, 3, and 4 tests:

Because coagulation hydrolysis reactions occur quickly, it will be important to have pH properly adjusted when coagulant addition and flash mixing occurs (i.e., simultaneous addition of chemicals). This is complicated by the fact that different coagulant dosages will cause pH variability. The solution is to complete a non-time-sensitive pre-test (before the actual jar testing is conducted) in which the operator first conditions the water with NaHCO_3 for alkalinity adjustment (per the protocol described in this testing plan) and then conducts the next steps:

1. Add coagulants to the 5 different jars as is expected to occur during jar testing;
2. Titrate concentrated acid (or base) to achieve the target pH condition (i.e., 6.5 units);
3. Record volume (mL) of acid or base titrant added to achieve the target pH for each jar;
4. Perform a 'live' test by adding titrant volumes to a small beaker/vial and placing these containers along-side their respective jar test beakers;
5. Add both (a) the pre-aliquot of acid or base per above and (b) the coagulant volume in the second beaker/vial into their appropriate jar simultaneously at the beginning of rapid mixing;
6. Monitor pH to confirm that the target pH condition is achieved within 0.1 units.

For cationic, nonionic, and anionic polymers:

Polymers are typically dosed full-scale as neat/original solution (not diluted). However, a stock/dosing solution still needs to be prepared so that it can be added in reasonable volumes into the jars. Follow the procedure below to create a polymer dosing solution.

1. Create a 2,000 mg/L stock/dosing solution as follows:
 - a. Using a stir plate, start mixing 998 mL DI water in a beaker such that there is a vortex formed in the middle of the beaker; using a warm stir plate (approximately 25 °C) will likely aid dissolution of the polymer (but is not required)
 - b. Slowly pipette 2 mL of polymer directly into the vortex with the tip of the pipette submerged

- c. After adding the entire 2 mL, remove the pipette tip from the water before releasing pressure from the pipettor tab (i.e., do not pull any solution into the tip)
 - d. Allow the polymer dosing solution to mix at this rapid state (and kept warm if using a warm stir plate) for at least 30 minutes prior to use. If clumps develop in the solution, allow the solution to continually stir until they completely dissolve.
2. Conduct the coagulant dosing during rapid mixing.
4. Add polymer at the beginning of the flocculation period (unless otherwise specified in the testing plan) by using a dosing syringe to collect the volume of dosing solution to be added into a jar, and setting the filled syringe next to the jar until it is ready to be added. Adding 1 mL of this stock solution provides a 1 mg/L dose in the jar, adding 2 mL provides a 2 mg/L dose, etc.



Technical Memorandum

Subject: Bull Run Water Jar Testing Results Round 1 (February 2019)

PWB Project: 30006570

BC Project: 152606

Date: February 19, 2019

To: Yone Akagi, Water Quality Manager

From: Alex Mofidi, Confluence

Reviewed by: Lynn Stephens, Brown and Caldwell



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CONTENTS

1. Jar Test Approach.....	3
1.1 Purpose	3
1.2 Testing Approach	3
1.3 Testing Timeline and Raw Water Characteristics.....	4
2. results.....	4
2.1 Coagulant-Only Tests	4
2.2 Flocculant-Aid Polymer Tests	8
3. Results and REcommendations.....	10
Attachment A: Raw Bull Run Water Sampling Sheet	A-1
Attachment B: Raw Data	B-1
Attachment C: Approach for Next Round of Testing.....	C-4

List of Figures

Figure 1. Coagulant-only results for turbidity and filterability index time.....	5
Figure 2. Coagulant-only results for color and UV transmittance.....	6
Figure 3. Coagulant-only results for total and dissolved organic carbon removal.....	7
Figure 4. Turbidity and filterability index time results with cationic, nonionic, and anionic polymers	8
Figure 5. DOC results with cationic, nonionic, and anionic polymers	9

List of Tables

Table 1. Raw Water Quality.....	4
Table C-1. Phase 1 Testing (Determine what dose should be tested further)	C-5
Table C-2. Phase 2 Testing (Determine ‘selected’ dose for later polymer tests).....	C-5
Table C-3. Phase 2 Testing (Determine ‘selected’ dose for later polymer tests).....	C-6

List of Abbreviations

2PIS	Second primary intake structure
ACH	aluminum chlorohydrate
AP	anionic polymer
BC	Brown and Caldwell
BRFP	Bull Run Filtration Project
CaCO ₃	calcium carbonate
Confluence	Confluence Engineering Group LLC
°C	degrees centigrade
CP	cationic polymer
DBP-SDS	disinfection by-product
DI	deionization
DOC	dissolved organic carbon
FI	filterability index
FP	formation potential
gpd	gallons per day
gph	gallons per hours
IP	ionic polymer
L	liter
lf	linear feet
mgd	million gallons per day
mg/L	milligrams per liter
NaHCO ₃	sodium bicarbonate
µm	micrometer
PACl	polyaluminum chloride
PWB	Portland Water Bureau
SDS	simulated distribution system
TBD	to be determined
TOC	total organic carbon
TM	technical memorandum
WTP	water treatment plant

1. JAR TEST APPROACH

This Technical Memorandum (TM) summarizes results from the first round of water sampling and jar tests conducted by the Portland Water Bureau (PWB) in February 2019 for the Bull Run Filtration Program. In general, procedures were followed according to the test plan (dated January 25, 2019). Any differences from the recommendations in the testing plan are provided in the text of this document (e.g., if a different dose range was used for a coagulant or polymer).

1.1 Purpose

The purpose of jar testing is to screen the performance of selected water treatment coagulants and polymers used during coagulation, flocculation, and sedimentation. This screening, to be conducted multiple times prior to the start of pilot testing, provides information that will be carried forward into the pilot testing program. The goal of screening these treatment chemicals is to determine dose ranges for primary coagulants (and polymers) that promote particle destabilization (i.e., pre-conditioning for filtration). Selection of coagulants (and polymers) is based on the ability to achieve an acceptable pre-filtration water quality. In general, this acceptance is based upon relatively low recordings for turbidity and filterability index (FI), and possibly additional indicators such as organics. Based on jar results, chemicals will be selected for further performance evaluation during dynamic, pilot testing conditions.

Although determining performance of coagulants is not a primary goal, some performance characteristics may be inferred from jar testing which includes dose ranges for coagulants that may (or may not) remove organic matter. More detailed organics removal and other performance characteristics, such as actual filter run performance and overall reduction in disinfection by-product (DBP) levels, will be evaluated during pilot testing.

1.2 Testing Approach

Testing was conducted by following a phased approach to evaluating coagulants and polymers. The overall testing approach included the following steps:

1. Collect 200-L of raw, Bull Run water using 10-L low-density polyethylene cubitainers;
2. Allow raw water to acclimate to laboratory room temperature prior to testing;
3. Adjust alkalinity of all raw water by adding 40 mg/L of sodium bicarbonate (NaHCO_3), resulting in an increase (from ambient) of 24 mg/L alkalinity as CaCO_3 ;
4. Test coagulants without pH adjustment over a range of doses;
5. Test coagulants after adjusting pH of coagulation to 6.5 units over a range of doses; and,
6. Test coagulants at a single dose, with adjusted pH of coagulation at 6.5 units, with flocculant aids consisting of cationic, anionic, and nonionic polymers.
7. Document impact of jar testing on turbidity and other indicators, including organic matter surrogates.
8. Perform a filterability index (FI) test to simulate the relative impacts that different chemical dosing strategies may have on filter performance.

1.3 Testing Timeline and Raw Water Characteristics

Attachment A summarizes characteristics of the raw Bull Run water collected from headworks (at 2PIS) for this test. Twenty, 10-L cubitainers of water were collected on December 2, 2018 and stored in two refrigerators at 2PIS between 0 to 10 °C. Water turbidity was approximately 0.3 NTU. Jar testing with this 200-L water sample was conducted across 7 days that spanned January and February, 2019. Raw water quality was sampled across the 7 days of testing, with results shown in **Table 1**.

Day Measured	pH (units)	Turbidity (NTU)	Apparent Color (units)	True Color ^a (units)	UV ₂₅₄ (1/cm)	DOC (mg/L)	TOC (mg/L)
1	7.0	0.38	15	15	0.060	1.5	2.0
2	7.0	0.98	29	7	0.072	2.0 ^b	1.5
3	7.0	0.48	16	10	0.067	1.5	1.5
4	7.3	0.24	14	11	0.065	1.5	1.4
5	6.8	0.49	17	10	0.064	1.4	1.4
6	6.8	0.58	18	12	0.069	1.4	1.4
7	7.0	0.33	18	11	0.065	1.4	1.4

a. Filtered at 0.45 µm

b. It was noticed that sample filters may have been adding organic carbon in error to DOC samples during some of these first tests (causing DOC>TOC errors), so procedures were changed to allow more of a filter rinse.

2. RESULTS

Coagulants tested included aluminum sulfate (alum), ferric chloride (ferric), polyaluminum chloride (PACl, PAX-18), and an aluminum chloralhydrate (ACH, PAX-XL19). Polymers included polyamine cationic polymer (Clarifloc C-309P), anionic polymer (Praestol 3040LTR), and nonionic polymer (Praestol 2500). The polydadmec polymer was not received in time for this testing, but may be evaluated in the future.

A very low raw water turbidity brought challenges to analyzing these results. Improvement from raw water turbidity was difficult to see, compounded by the detection limit of the bench-top turbidimeter. Furthermore, pH adjustment did not hold for these tests and, as pH ranged, it possibly impacted the efficiency of some of the coagulants. When analyzing results, focus was placed on evaluating if turbidity became worse and/or the relative results of FI testing (i.e., if FI results are worse than the control). Other information, such as organic matter removal, was also assessed.

In addition to low turbidity, Phase 1 jar testing involved additional challenges. These included chemical dosing accuracy and developing repeatable FI test results. Because of these Phase 1 challenges, Phase 2 tests were conducted somewhat as a repeat of Phase 1 (e.g., a similar, wide range of chemical dosages were evaluated during Phase 2). Therefore, Phase 1 results are not analyzed in detail here.

2.1 Coagulant-Only Tests

Initial test results (Phase 2) are presented below in **Figure 1**. Control jar (no chemicals) turbidity and FI numbers were 0.43 NTU and 6 minutes for alum, ferric and PACl, and 0.5 NTU and 16 minutes for ACH. Adjusting pH was attempted (to 6.5 units), but could not be held through settling. Turbidity results are shown in blue and FI results are shown in orange.

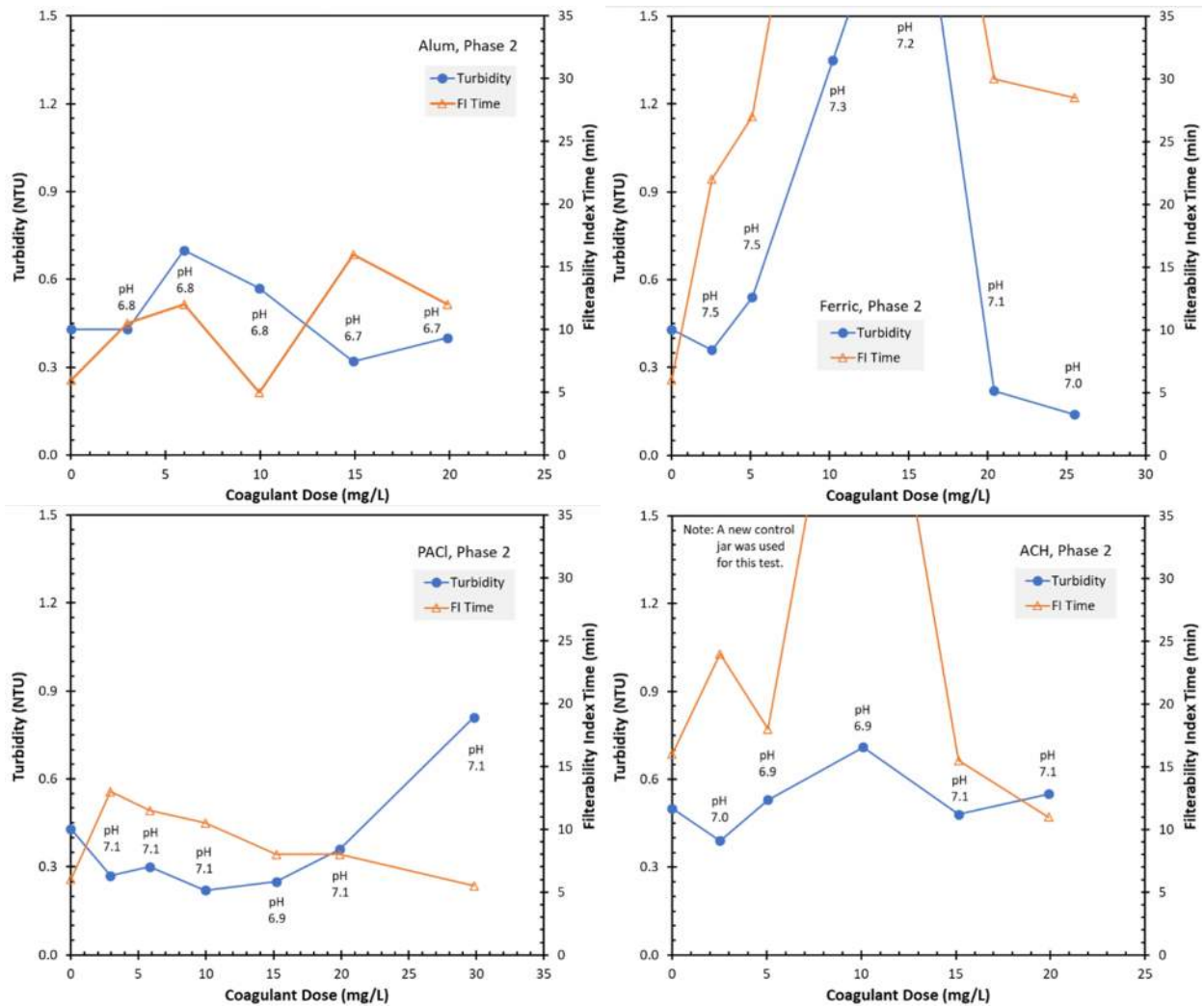


Figure 1. Coagulant-only results for turbidity and filterability index time

Results showing (clockwise from upper-left) alum, ferric, ACH, and PACl settled water turbidity, FI time, and recorded pH

Note that data exceeding the top of each graph were plotted that way to (a) keep y-axes similar between graphs, and (b) not focus on 'poor performance' conditions represented by elevated datapoints. An optimal result is expected to occur at the best (low) turbidity and (low) FI time combinations. Results of these tests are summarized as follows:

- Alum showed good performance between 3 and 6 mg/L and at 20 mg/L. Filterability time was much lower at 10 mg/L, but it showed greater turbidity and may have been a mis-read because the FI times before (6 mg/L) and after (15 mg/L) were much greater.
- Ferric performed best at 3 mg/L. It also had good turbidity performance at ≥ 20 mg/L, but those elevated dosages had very high FI times, indicating filter runs may be impacted.
- PACl almost performed almost as a flat-line for turbidity out to 20 mg/L. The FI time peaked at a low dose (3 mg/L), and decreased consistently up through the greatest dose (30 mg/L). Where turbidity and FI time cross (approximately between 15 to 20 mg/L) may be the optimum dose.

- ACH showed good turbidity performance at both a low dose (between 3 and 5 mg/L) and a high dose (between 15 and 20 mg/L). FI time was good at 5, 15, and 20 mg/L.

In addition to turbidity and FI time, removal of organic matter was also evaluated. Surrogates for organic matter included apparent and true color, ultraviolet absorbance at 254-nm (UV₂₅₄), and dissolved and total organic carbon (DOC, TOC). Apparent color and TOC were not filtered, while true color and DOC were filtered through a 0.45 µm filter prior to analysis). UV₂₅₄ absorbance readings were made before and after filtering through a 0.45 µm filter. Although organic carbon removal may not be the primary goal of jar testing, it can help determine which coagulants may perform well for both particulate and organic matter removal. Further analysis of this performance would be carried out during pilot testing.

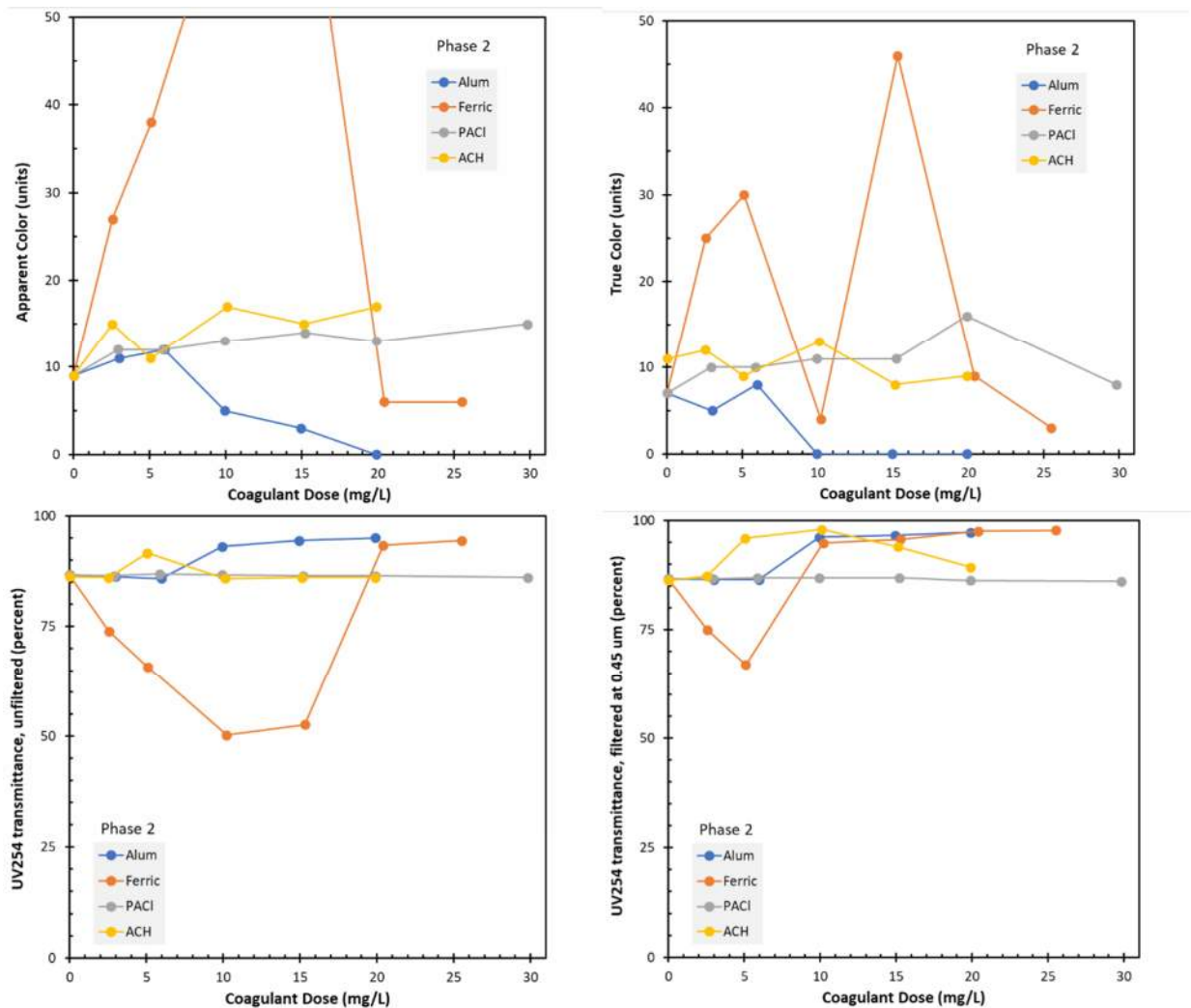


Figure 2. Coagulant-only results for color and UV transmittance

Unfiltered (apparent color) and percent UV₂₅₄ transmittance (calculated from UV₂₅₄ absorbance data) on the left, and filtered (at 0.45 µm) true color and percent UV₂₅₄ transmittance on the right

Color and UV₂₅₄ results are shown above in **Figure 2**. Percent UV₂₅₄ transmittance values were calculated from UV absorbance measurements as a more practical result measure. Interpreting results from these measurements was difficult as unfiltered and filtered surrogates showed either very little differences

from the control, or showed dramatic change in mid-level coagulant dosages (e.g., significant increase in color and decrease in UV transmittance for ferric), only to recover to levels similar to the control. Upon review of this data, it does seem that alum performed best: a dose of 10 mg/L removed apparent and true color, and seemed to allow high UV₂₅₄ transmittance. ACH also provided high UV₂₅₄ transmittance at a low dose based on 0.45- μ m filtered samples.

Coagulant removal of TOC and DOC is shown below in **Figure 3**. Graphed data show TOC and DOC values based on coagulant dose and the percentage value data (shown on the DOC graph) indicate the percentage removal at that data point when compared to the control. Both show consistent responses across the dosages tested, but different removal levels. A problem with this data is that DOC is removed at a rate much greater than TOC. Although this is not a problem in and of itself, the issue was that DOC numbers decreased while TOC numbers remained the same (i.e., for a specific condition, DOC decreased while the TOC number did not change). The reason this may have happened was that TOC was bound to floc or particles suspended in the water column during sampling. When samples were then processed, the 0.45- μ m filter used for DOC samples removed those agglomerated, TOC-containing particles. However, TOC samples (unfiltered) analyzed the entire water sample. Data show that alum and ferric consistently removed TOC and DOC as dosage increased while PACI did not remove either. ACH may have bound organics which remained in the water column and then were removed during 0.45- μ m sample filtration for DOC processing (i.e., DOC removal was observed but very little TOC removal was achieved). Alum and ACH achieved greater DOC removal at lower dosages when compared to ferric.

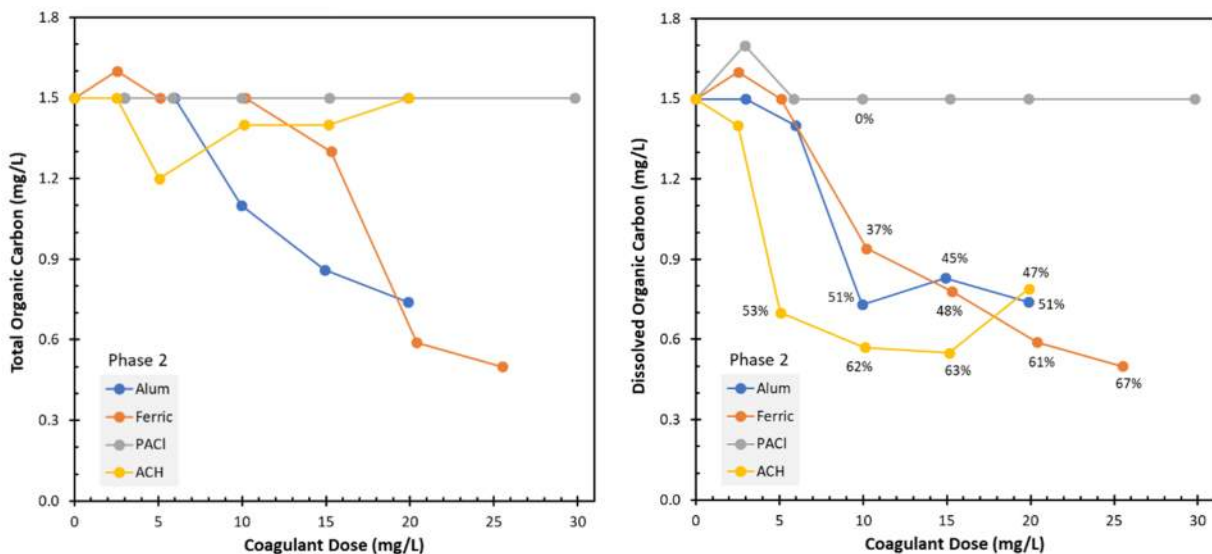


Figure 3. Coagulant-only results for total and dissolved organic carbon removal

Based on all of the above results, coupled with the approach of dropping one of the coagulants from the next testing round, PACI was dropped from further analysis. Alum, ferric, and ACH were chosen to be tested further with polymers based on the following reasons:

- Alum, ferric, and ACH showed good particle removal and FI time data at low dosages.
- Alum and ferric showed good TOC and DOC removal at elevated dosages.

- ACH showed good DOC removal at low doses, but not TOC removal – possibly because floc-bound organics entered samples and were removed by 0.45- μ m filtration (i.e., organics removal may not occur during settling but may be achieved during a later filtration step).
- PACI did not show measurable organics removal, and likely required a much greater operating dose for particle removal when compared to ACH.

Based on the above results, the following dosages were selected to be evaluated in combination with polymers: alum at 6 mg/L, ferric at 5 mg/L, and ACH at 5 mg/L.

2.2 Flocculant-Aid Polymer Tests

Data showing the impact of polymer addition as a flocculant aid on turbidity removal and FI times are shown in **Figure 4**. All polymers were added at the beginning of the flocculation stage (after rapid mixing was completed). Cationic polymer was added up to 2 mg/L while the nonionic and anionic polymers were added up to 0.16 mg/L.

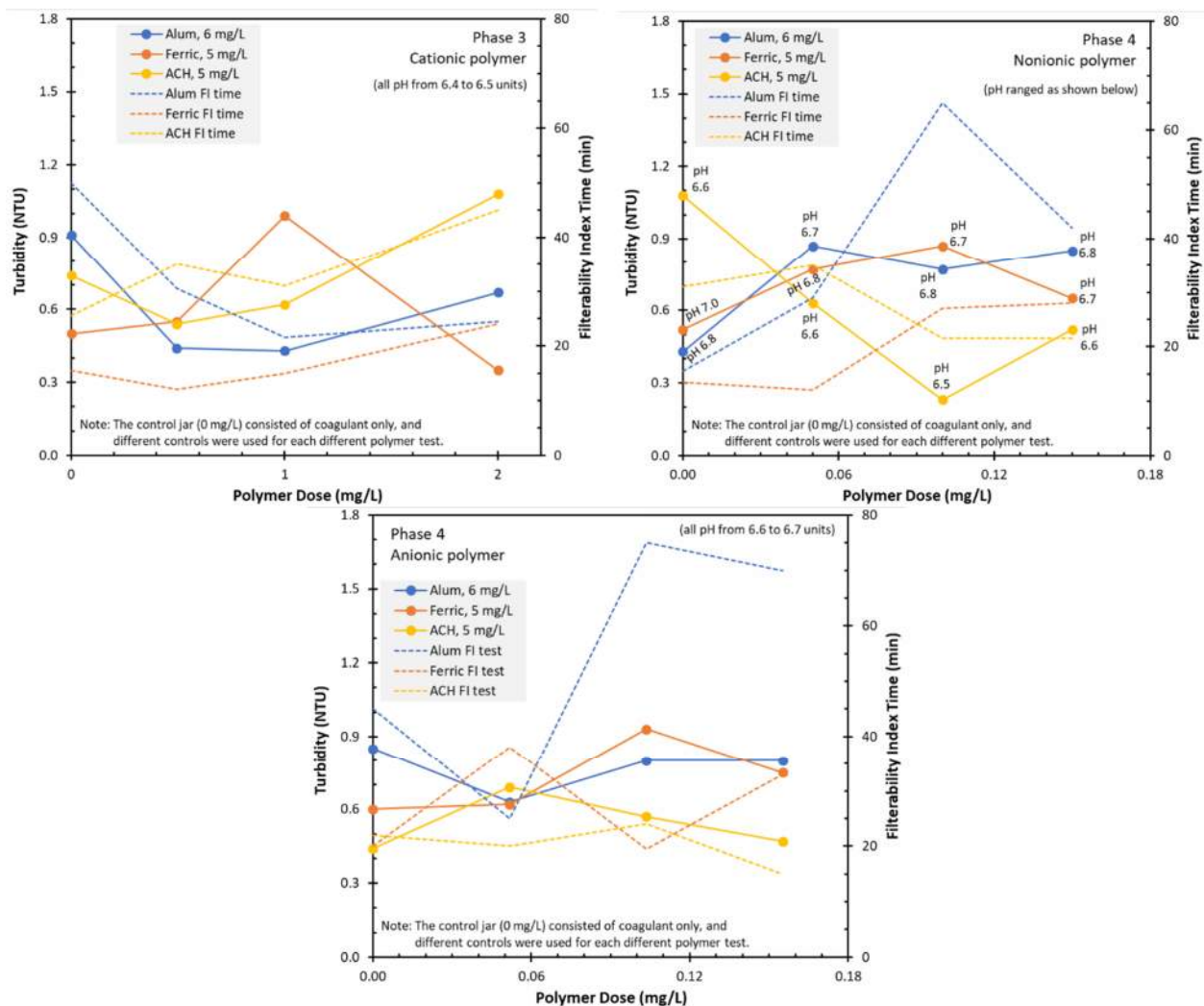


Figure 4. Turbidity and filterability index time results with cationic, nonionic, and anionic polymers

Upon reviewing the polymer data, it is very difficult to see significant impact at this low turbidity level. It seems that the cationic polymer helped the alum equivalently at doses of 0.5 and 1 mg/L (turbidity and FI times were lower than the alum-only control), but it was difficult to see benefit to the ferric or ACH.

Nonionic polymer helped ACH to achieve a lower turbidity and FI time, but nonionic polymer did not improve results with alum and ferric.

There was no significant benefit from adding anionic polymer.

Polymer dose impacts on DOC reduction are shown in **Figure 5**. Each of the polymer dosages showed improvement in DOC removal. Cationic and nonionic polymers showed the most benefit at a low dose (increased dose showed limited improvement). Overall, anionic polymer did not provide much benefit compared to the control. Result interpretation was difficult as raw water quality was measured to contain 1.4 mg/L DOC but several control jars exceeded this amount.

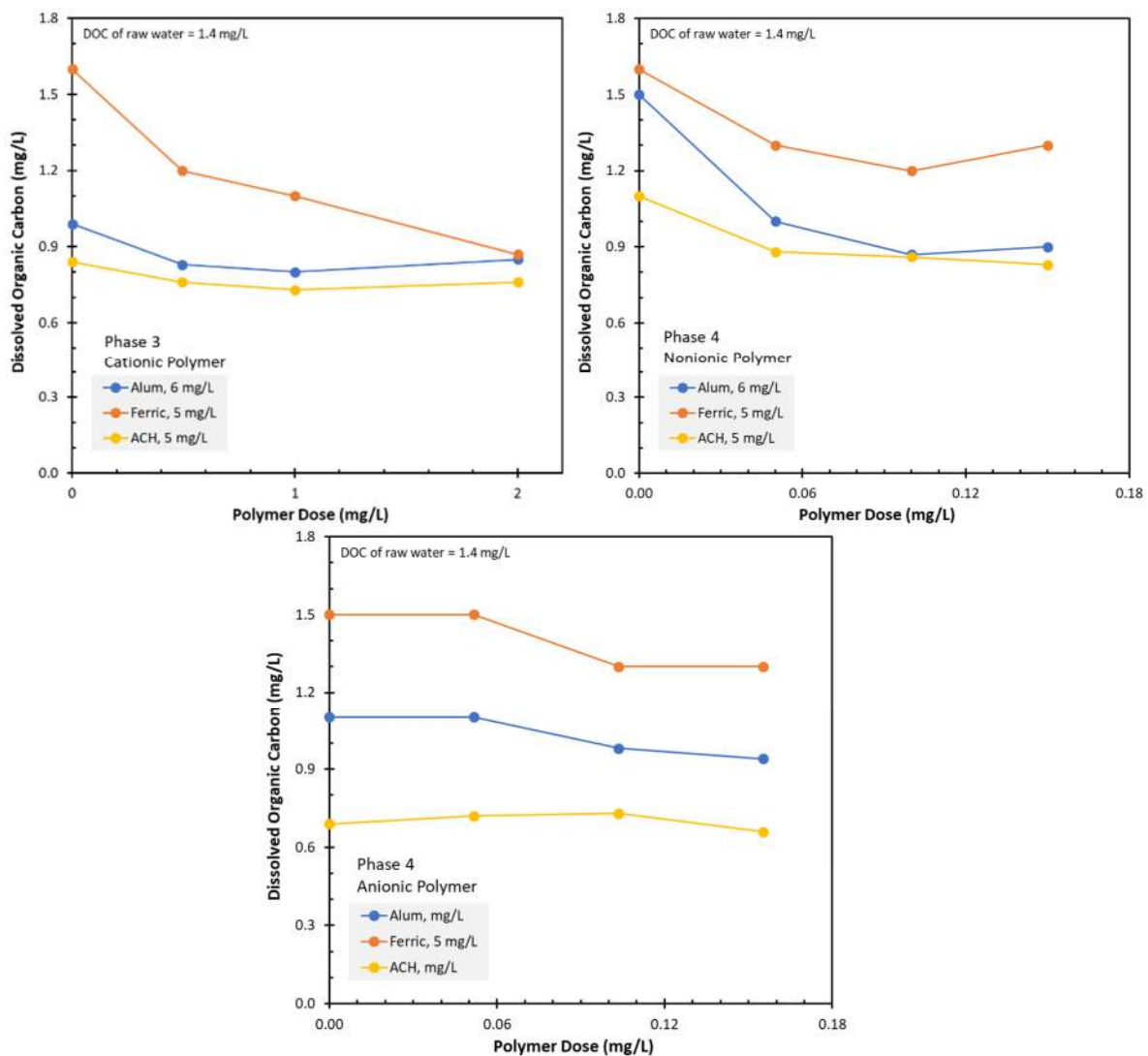


Figure 5. DOC results with cationic, nonionic, and anionic polymers

3. RESULTS AND RECOMMENDATIONS

Overall, testing has produced a great deal of useful data. Although low-turbidity Bull Run water is a challenge to treat and requires a high coagulant dose to produce visually-settleable floc, results are showing that low coagulant doses are showing potential for pilot testing selection. Below are a summary of findings from this first round of testing, along with recommendations for future tests.

For assessing turbidity removal and FI time performance, the following results were observed.

- Coagulation pH was not optimized and may have impacted test results. Some contribution to sub-optimal conditions may have been from adding alkalinity, which also increased pH.
- It was difficult to assess coagulants by turbidity alone because raw water turbidity was very low.
- Alum showed good turbidity and FI times at both low and high dosages.
- Ferric showed good turbidity removal at low and high dosages, but FI times were much greater than alum.
- PACI required comparably greater dosages to achieve good turbidity and FI time.

For assessing organics removal, the following results were observed.

- There were discrepancies between DOC and TOC data, possibly because floc particles were entrained in collected samples (floc particles were then removed by a subsequent filter step).
- Color was an inconsistent indicator for organics removal.
- Alum and ACH removed similar or greater levels of DOC when compared to ferric.

Recommendations are listed below.

- Test all coagulants at least one more time. Likely discontinue ferric tests after this next testing event if it does not show better results.
- Remove anionic polymer from future testing.
- Test a polydadmec polymer (up to 3 mg/L) and the nonionic polymer (up to 0.2 mg/L).
- A full alkalinity boost to all samples is not needed, and because it also increased pH conditions, alkalinity boosting should be adjusted. First, reduce the alkalinity dose by 75% from 40 mg/L to 10 mg/L of sodium bicarbonate. Second, add this alkalinity only to the jars with elevated alum or ferric is added (e.g., based on expected Bull Run alkalinity, alkalinity boosting is only needed in jars with >10 mg/L alum or >8 mg/L ferric). PACI and ACH jars do not need alkalinity boosting.
- For the next testing round, conduct as follows:
 - For Phase 1, test all coagulants under the same ranges as before, adjusting alkalinity per above only for the upper alum and ferric doses.
 - For Phase 2, select fine-tune doses based on results from Phase 1 as follows
 - Jar 1: Run a control jar (0 mg/L),
 - Jars 2, 3, and 4: Bracket the chosen dose with 3 jars without pH adjustment (e.g., if 5 mg/L was 'optimum', then doses to run may be 3, 5, and 7 mg/L),

- Jars 5 and 6: Duplicate the high and low dose (e.g., 3 and 7 mg/L) along with adjusting pH to 6.5 units in both. This will reduce pH adjustment jars while still evaluating the benefits of pH adjustment.
- For Phase 3 coagulant with polydadmec tests, follow the same approach as above for Phase 2 (i.e., run a control jar, a range of three polydadmec doses in three jars, and two jars of high/low polydadmec doses with pH adjustment).
- For Phase 4, repeat Phase 3 with nonionic polymer.
- To ensure enough water is available, increase water collection to 240 L (24 x 10-L carboys) for jar testing. Additional water may also be needed for ozone bench testing.
- Although it is unclear if the full 60-min is required for full settling, it is anticipated to cause too much additional work to properly assess different settling times (it may require 2 days or more of testing). Therefore, it is recommended to keep the 60-min settling time.
- If possible, obtain a more sensitive turbidimeter.
- Collect the same samples in the next round of testing, but if color results do not improve, discontinue sampling for color in future tests.
- Continue to perform tests at room temperature.
- Use all polymers within 24 hours of stock prep based on direction from the chemical vendor.
- Because the testing team noted challenges using 100 mL for FI testing (i.e., too much water for the filter size), reduce the FI sample size to a volume that results in one single pour.

Attachment A: Raw Bull Run Water Sampling Sheet

List of collection times and water quality

Water Quality Filtration Pilot Lab Project					
APIS		Date: 12/3/18		Sampler: Sarah Matthecheck	
ID	Start Time	Start Turbidity	End Time	End Turbidity	Bulk: 10L cube
F1	1108	0.320	1109	↑	X
F2	1109		1110		X
F3	1110		1111		X
F4	1111		1113		X
F5	1114		1115		X
F6	1115		1116		X
F7	1116		1117		X
F8	1117		1118		X
F9	1119		1120		X
F10	1120		1121		X
F11	1122		1123		X
F12	1123		1124		X
F13	1124		1125		X
F14	1126		1127		X
F15	1127		1128		X
F16	1128		1129		X
F17	1130		1131		X
F18	1132		1133		X
F19	1133		1134		X
F20	1134	↓	1135	0.318	X
Samples stored between 0-10 °C?		<input checked="" type="checkbox"/> Yes		<input type="checkbox"/> No	
Signature: Sarah Matthecheck			Phone: 503-823-1574		

Attachment B: Raw Data

Bull Run Water Jar Testing Results: Round 1

Phase	Chemical	Coag Dose (mg/L)	Poly Dose (mg/L)	Raw or Settled Water										FI Test			
				pH	Turb (ntu)	Color, App	Color, True	UV254	%T	UV254 (0.45um)	%T (0.45 um)	DOC (mg/L)	%DOC Rem	TOC (mg/L)	%TOC Rem	Turb (ntu)	Time (min)
Raw Water	Day 1			7.0	0.38	15	15	0.060	87.1			1.5		2.0			
	Day 2			7.0	0.98	29	7	0.072	84.7			2.0		1.5			
	Day 3			7.0	0.48	16	10	0.067	85.7			1.5		1.5			
	Day 4			7.3	0.24	14	11	0.065	86.1			1.5		1.4			
	Day 5			6.8	0.49	17	10	0.064	86.3			1.4		1.4			
	Day 6			6.8	0.58	18	12	0.069	85.3			1.4		1.4			15
	Day 7			7.0	0.33	18	11	0.065	86.1			1.4		1.4		0.2	12
Phase 1 (40 mg/L NaHCO ₃ , ambient pH)	Alum	0		7.6	0.34	15	10	0.065	86.1	0.070	85.1	1.5		1.4		0.3	8
		1		7.6	0.32	15	3	0.066	85.9	0.068	85.5	1.4		1.4			9
		3		7.1	0.34	14	11	0.062	86.7	0.065	86.1	1.5		1.4			8
		6		7.5	0.52	14	10	0.062	86.7	0.063	86.5	1.5		1.4		0.5	7
		10		7.4	0.78	17	4	0.069	85.3	0.039	91.4	1.6		1.4		0.4	28
		15		7.2	0.43	3	3	0.025	94.4	0.023	94.8	0.8		0.9			
	Ferric Chloride	0		7.8	0.30	11	9	0.062	86.7	0.062	86.7	1.4		1.4		0.4	11
		2.6		7.5	0.42	25	21	0.127	74.6	0.125	75.0	1.4		1.4		0.4	8
		5		7.4	0.56	37	30	0.177	66.5	0.170	67.6	1.4		1.4		0.4	12
		10		7.1	1.12	59	3	0.293	50.9	0.022	95.1	1.3		1.4		1.1	12
		15		6.9	0.22	4	0	0.040	91.2	0.010	97.7	0.6		0.7		0.4	10
		20		6.6	0.18	3	0	0.021	95.3	0.008	98.2	0.6		0.6		0.1	21
	PACI (PAX-18)	0		7.6	0.37	11	7	0.064	86.3	0.062	86.7	1.6		1.5		0.3	9
		6		7.5	0.58	12	7	0.066	85.9	0.066	85.9	1.6		1.5		0.3	19
		29		7.0	0.39	0	4	0.029	93.5	0.010	97.7	0.7		0.8		0.1	30
		58		6.6	0.55	13	9	0.066	85.9	0.013	97.1	0.6		1.5		0.6	77
		88		0.0													
		117		0.0													
	ACH (PAX-XL19)	0		7.6	0.31	7	3	0.063	86.5	0.063	86.5	1.6		1.5		0.3	26
		5		7.6	0.61	12	2	0.066	85.9	0.051	88.9	1.4		1.5		0.4	20
		10		7.5	0.24	9	7	0.025	94.4	0.014	96.8	0.7		0.9		0.2	23
		15		7.4	0.15	26	0	0.019	95.7	0.012	97.3	0.6		0.8		0.2	32
		20		7.4	0.21	2	0	0.034	92.5	0.009	97.9	0.6		1.0		0.1	28
		30		7.4	0.71	9	7	0.066	85.9	0.013	97.1	0.7		1.5		0.2	75

Phase	Chemical	Coag Dose (mg/L)	Poly Dose (mg/L)	Raw or Settled Water										FI Test			
				pH	Turb (ntu)	Color, App	Color, True	UV254	%T	UV254 (0.45um)	%T (0.45 um)	DOC (mg/L)	%DOC Rem	TOC (mg/L)	%TOC Rem	Turb (ntu)	Time (min)
Phase 2 (40 mg/L NaHCO ₃ , pH target 6.5)	Alum	0		6.8	0.43	9	7	0.062	86.7	0.062	86.7	1.5		1.5		0.6	6
		3		6.8	0.43	11	5	0.064	86.3	0.063	86.5	1.5	0.0	1.5	0.0	0.4	11
		6		6.8	0.70	12	8	0.066	85.9	0.063	86.5	1.4	6.7	1.5	0.0	0.6	12
		10		6.8	0.57	5	0	0.031	93.1	0.017	96.2	0.7	51.3	1.1	26.7	0.5	5
		15		6.7	0.32	3	0	0.025	94.4	0.015	96.6	0.8	44.7	0.9	42.7	0.3	16
		20		6.7	0.40	0	0	0.022	95.1	0.012	97.3	0.7	50.7	0.7	50.7	0.3	12
	0	0		6.8	0.43	9	7	0.062	86.7	0.062	86.7	1.5		1.5		0.6	6
	Ferric Chloride	2.6		7.5	0.36	27	25	0.131	74.0	0.125	75.0	1.6	-6.7	1.6	-6.7	0.2	22
		5		7.5	0.54	38	30	0.182	65.8	0.174	67.0	1.5	0.0	1.5	0.0	0.3	27
		10		7.3	1.35	66	4	0.299	50.2	0.023	94.8	0.9	37.3	1.5	0.0	1.0	63
		15		7.2	2.16	69	46	0.279	52.6	0.019	95.7	0.8	48.0	1.3	13.3	0.2	66
		20		7.1	0.22	6	9	0.030	93.3	0.011	97.5	0.6	60.7	0.6	60.7	0.2	30
		26		7.0	0.14	6	3	0.025	94.4	0.010	97.7	0.5	66.7	0.5	66.7	0.1	29
	0	0		6.8	0.43	9	7	0.062	86.7	0.062	86.7	1.5		1.5		0.6	6
	PACI (PAX-18)	3		7.1	0.27	12	10	0.063	86.5	0.062	86.7	1.7	-13.3	1.5	0.0	0.1	13
		6		7.1	0.30	12	10	0.061	86.9	0.061	86.9	1.5	0.0	1.5	0.0	0.2	12
		10		7.1	0.22	13	11	0.062	86.7	0.061	86.9	1.5	0.0	1.5	0.0	0.2	11
		15		6.9	0.25	14	11	0.063	86.5	0.061	86.9	1.5	0.0	1.5	0.0	0.2	8
		20		7.1	0.36	13	16	0.063	86.5	0.064	86.3	1.5	0.0	1.5	0.0	0.3	8
		30		7.1	0.81	15	8	0.065	86.1	0.065	86.1	1.5	0.0	1.5	0.0	0.6	6
	ACH (PAX-XL19)	0.0		7.1	0.50	9	11	0.064	86.3	0.064	86.3	1.5		1.5		0.2	16
		2.5		7.0	0.39	15	12	0.065	86.1	0.059	87.3	1.4	6.7	1.5	0.0	0.3	24
		5.1		6.9	0.53	11	9	0.038	91.6	0.018	95.9	0.7	53.3	1.2	20.0	0.2	18
		10.1		6.9	0.71	17	13	0.066	85.9	0.009	97.9	0.6	62.0	1.4	6.7	0.1	60
		15.1		7.1	0.48	15	8	0.065	86.1	0.027	94.0	0.6	63.3	1.4	6.7	0.5	16
		19.9		7.1	0.55	17	9	0.065	86.1	0.049	89.3	0.8	47.3	1.5	0.0	0.6	11

Phase 3 (40 mg/L NaHCO ₃ , pH target 6.5, Cationic Polymer Clarifloc C309P)	Alum	6	0.0	6.4	0.91	17	5	0.066	85.9	0.025	94.4	1.0		1.6		0.4	50
		6	0.5	6.5	0.44	11	7	0.038	91.6	0.019	95.7	0.8	16.2	1.2	25.0	0.3	31
		6	1.0	6.5	0.43	12	1	0.037	91.8	0.024	94.6	0.8	19.2	1.2	25.0	0.3	22
		6	2.0	6.4	0.67	15	0	0.045	90.2	0.015	96.6	0.9	14.1	1.2	25.0	0.4	25
	Ferric Chloride	5	0.0	6.4	0.50	38	30	0.184	65.5	0.149	71.0	1.6		1.6		0.4	16
		5	0.5	6.5	0.55	38	4	0.182	65.8	0.024	94.6	1.2	25.0	1.5	6.3	0.5	12
		5	1.0	6.5	0.99	41	4	0.185	65.3	0.019	95.7	1.1	31.3	1.4	12.5	0.7	15
		5	2.0	6.5	0.35	12	1	0.046	89.9	0.019	95.7	0.9	45.6	0.9	43.1	0.1	24
	ACH	5	0.0	6.5	0.74	12	3	0.043	90.6	0.013	97.1	0.8		1.3		0.2	26

Bull Run Water Jar Testing Results: Round 1

Phase	Chemical	Coag Dose (mg/L)	Poly Dose (mg/L)	Raw or Settled Water										FI Test			
				pH	Turb (ntu)	Color, App	Color, True	UV254	%T	UV254 (0.45um)	%T (0.45 um)	DOC (mg/L)	%DOC Rem	TOC (mg/L)	%TOC Rem	Turb (ntu)	Time (min)
	(PAX-XL19)	5	0.5	6.5	0.54	14	1	0.043	90.6	0.033	92.7	0.8	9.5	1.2	7.7	0.2	35
		5	1.0	6.5	0.62	14	1	0.047	89.7	0.013	97.1	0.7	13.1	1.2	7.7	0.2	31
		5	2.0	6.5	1.08	20	2	0.066	85.9	0.014	96.8	0.8	9.5	1.4	-7.7	0.2	45
Phase 4i (40 mg/L NaHCO ₃ , pH target 6.5, Nonionic Polymer Praestol 2500)	Alum	6	0.00	6.8	0.43	14	8	0.063	86.5	0.056	87.9	1.5		1.5		0.3	16
		6	0.05	6.7	0.87	16	3	0.066	85.9	0.025	94.4	1.0	33.3	1.6	-6.7	0.4	29
		6	0.10	6.8	0.77	17	6	0.064	86.3	0.018	95.9	0.9	42.0	1.5	0.0	0.2	65
		6	0.15	6.8	0.85	16	1	0.064	86.3	0.021	95.3	0.9	40.0	1.6	-6.7	0.2	42
	Ferric Chloride	5	0.00	7.0	0.52	38	31	0.187	65.0	0.163	68.7	1.6		1.7		0.4	14
		5	0.05	6.8	0.77	36	5	0.184	65.5	0.026	94.2	1.3	18.8	1.6	5.9	0.4	12
		5	0.10	6.7	0.87	38	24	0.191	64.4	0.123	75.3	1.2	25.0	1.6	5.9	0.4	27
		5	0.15	6.7	0.65	37	13	0.184	65.5	0.058	87.5	1.3	18.8	1.6	5.9	0.4	28
	ACH (PAX-XL19)	5	0.00	6.6	1.08	10	0	0.043	90.6	0.040	91.2	1.1		1.6		0.2	31
		5	0.05	6.6	0.63	6	0	0.028	93.8	0.016	96.4	0.9	20.0	1.2	25.0	0.1	35
		5	0.10	6.5	0.23	4	5	0.029	93.5	0.018	95.9	0.9	21.8	1.1	31.3	0.1	22
		5	0.15	6.6	0.52	6	7	0.024	94.6	0.022	95.1	0.8	24.5	1.0	37.5	0.1	22
Phase 4ii (40 mg/L NaHCO ₃ , pH target 6.5, Anionic Polymer Praestol 3040)	Alum	6	0.00	6.7	0.85	16	3	0.066	85.9	0.031	93.1	1.1		1.7		0.3	45
		6	0.05	6.7	0.63	14	0	0.066	85.9	0.028	93.8	1.1	0.0	1.6	5.9	0.4	25
		6	0.10	6.7	0.80	16	3	0.065	86.1	0.021	95.3	1.0	10.9	1.5	11.8	0.3	75
		6	0.16	6.7	0.80	16	6	0.065	86.1	0.055	88.1	0.9	14.5	1.5	11.8	0.2	70
	Ferric Chloride	5	0.00	6.7	0.60	40	31	0.188	64.9	0.157	69.7	1.5		1.6		0.3	20
		5	0.05	6.7	0.62	39	27	0.183	65.6	0.151	70.6	1.5	0.0	1.5	6.3	0.3	38
		5	0.10	6.7	0.93	41	9	0.197	63.5	0.035	92.3	1.3	13.3	1.5	6.3	0.4	20
		5	0.16	6.6	0.75	40	5	0.191	64.4	0.029	93.5	1.3	13.3	1.4	12.5	0.4	33
	ACH (PAX-XL19)	5	0.00	6.6	0.44	10	2	0.038	91.6	0.019	95.7	0.7		1.1		0.2	22
		5	0.05	6.6	0.69	12	5	0.038	91.6	0.035	92.3	0.7	-4.3	1.2	-9.1	0.2	20
		5	0.10	6.6	0.57	10	6	0.035	92.3	0.018	95.9	0.7	-5.8	1.1	0.0	0.1	24
		5	0.16	6.6	0.47	11	6	0.037	91.8	0.014	96.8	0.7	4.3	1.0	9.1	0.1	15

Attachment C: Approach for Next Round of Testing

Based on Project Team Meeting Held on February 20, 2019

Round 2 Testing Approach

- Implement a process to evaluate jars at lower temperature, but keep consistency so that different gangs of jars do not experience different temperatures (e.g., do not let the water get warmer for each subsequent jar test completed). For quality control, be sure to measure temperature during jar testing.
- Adjust FI tests as follows:
 - Run raw water sample as before, and also run DI water control sample each day.
 - Have funnel sitting on top of a 50-mL graduated cylinder
 - Add 25 mL, and when 23 mL volume passes, add a second 25 mL (50 mL total)
 - Without stopping the timer, record time it took to pass both 23 mL and 46 mL
- For Phases 2 and later, have a 7th jar as a raw Bull Run water control (no chemicals and no mixing in the 7th jar)
- As a group, consider removing one of the coagulants from further testing after Phase 2
- Phase 2 jar test dosages are below in Table C-1.

Table C-1. Phase 1 Testing (Determine what dose should be tested further)

Condition	Chemical	Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6
1a	Alum	0	3	6	9	12	15
1b	Ferric chloride	0	3	6	9	8	10
1c	PACl	0	3	6	9	10	15
1d	ACH	0	3	6	9	10	15

- Phase 2 tests (below in Table C-2) will repeat 3 coagulant dosages from all 4 coagulants to explore the dose that best performs during Phase 1. Best performance is estimated based on relatively low turbidity and FI performance.

Table C-2. Phase 2 Testing (Determine 'selected' dose for later polymer tests)

Condition	Chemical	Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6
2a	Alum	Coag X	Coag Y	Coag Z	Coag X pH 6.5	Coag Y pH 6.5	Coag Z pH 6.5
2b	Ferric chloride	Coag X	Coag Y	Coag Z	Coag X pH 6.5	Coag Y pH 6.5	Coag Z pH 6.5
2c	PACl	Coag X	Coag Y	Coag Z	Coag X pH 6.5	Coag Y pH 6.5	Coag Z pH 6.5
2d	ACH	Coag X	Coag Y	Coag Z	Coag X pH 6.5	Coag Y pH 6.5	Coag Z pH 6.5

- After completion of Phase 2, a coagulant is likely to be removed from further tests (only 3 coagulants will be carried forward).
- The approach to Phase 3 tests was slightly changed from the discussion during our meeting at PWB on 20 Feb and are described as follows:
 - Evaluate a control (0 poly) and 4 polymer doses without pH adjustment
 - Evaluate 2 conductions with pH adjustment to 6.5 units
 - This can be modified as the group wishes (let's discuss)
- Phase 3 tests (with polydadmec) will assess a single coagulant dose (approximate best dose from Phase 2) for each coagulant.

Table C-3. Phase 3 Testing polydadmec polymer (with one coagulant dose)

Condition	Chemical	Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6
3a	Coagulant 1	Coag dose 0 Poly	Coag dose 0.5 Poly	Coag dose 1.0 Poly	Coag dose 1.5 Poly	Coag dose pH 6.5 0.50 Poly	Coag dose pH 6.5 1.5 Poly
3b	Coagulant 2	Coag dose 0 Poly	Coag dose 0.5 Poly	Coag dose 1.0 Poly	Coag dose 1.5 Poly	Coag dose pH 6.5 0.50 Poly	Coag dose pH 6.5 1.5 Poly
3c	Coagulant 3	Coag dose 0 Poly	Coag dose 0.5 Poly	Coag dose 1.0 Poly	Coag dose 1.5 Poly	Coag dose pH 6.5 0.50 Poly	Coag dose pH 6.5 1.5 Poly

- Phase 3 tests (with nonionic polymer) will assess the same coagulant dose (same as with the polydadmec tests, the approximate best dose from Phase 2) for each coagulant.

Table C-4. Phase 3 Testing nonionic polymer (with one coagulant dose)

Condition	Chemical	Jar 1	Jar 2	Jar 3	Jar 4	Jar 5	Jar 6
3d	Coagulant 1	Coag dose 0 Poly	Coag dose 0.05 Poly	Coag dose 0.10 Poly	Coag dose 0.15 Poly	Coag dose pH 6.5 0.05 Poly	Coag dose pH 6.5 0.10 Poly
3e	Coagulant 2	Coag dose 0 Poly	Coag dose 0.05 Poly	Coag dose 0.10 Poly	Coag dose 0.15 Poly	Coag dose pH 6.5 0.05 Poly	Coag dose pH 6.5 0.10 Poly
3f	Coagulant 3	Coag dose 0 Poly	Coag dose 0.05 Poly	Coag dose 0.10 Poly	Coag dose 0.15 Poly	Coag dose pH 6.5 0.05 Poly	Coag dose pH 6.5 0.10 Poly



Technical Memorandum

Subject: Bull Run Water Jar Testing Results Round 2 (March 2019)

PWB Project: 30006570

BC Project: 152606

Date: April 7, 2019

To: Yone Akagi, Water Quality Manager

From: Alex Mofidi, Confluence

Reviewed by: Lynn Stephens, Brown and Caldwell



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CONTENTS

1. Jar Test Approach.....	3
1.1 Purpose	3
1.2 Testing Approach	3
1.3 Testing Timeline and Raw Water Characteristics.....	4
2. Results.....	5
2.1 Coagulant-Only Tests	5
2.2 Flocculant-Aid Polymer Tests	8
3. Summary	11
Attachment A: Raw Data	A-1

List of Figures

Figure 1. Coagulant-only results for turbidity, before and after FI test, and filterability index time	6
Figure 2. Phase Two - Coagulant-only results for unfiltered and filtered UV transmittance.....	7
Figure 3. Phase Two - Coagulant-only results for TOC and DOC	8
Figure 4. Turbidity and filterability index time results with Clarifloc C-308P.....	9
Figure 5. Turbidity and filterability index time results with Clarifloc C-309P.....	10
Figure 6. DOC results with Clarifloc C-308P and C-309P	11

List of Tables

Table 1. Raw Water Quality.....	4
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List of Abbreviations

2PIS	Second primary intake structure
ACH	aluminum chlorohydrate
AP	anionic polymer
BC	Brown and Caldwell
BRFP	Bull Run Filtration Project
CaCO ₃	calcium carbonate
Confluence	Confluence Engineering Group LLC
°C	degrees centigrade
CP	cationic polymer
DBP-SDS	disinfection by-product
DI	deionization
DOC	dissolved organic carbon
FI	filterability index
FP	formation potential
gpd	gallons per day
gph	gallons per hours
IP	ionic polymer
L	liter
lf	linear feet
mgd	million gallons per day
mg/L	milligrams per liter
NaHCO ₃	sodium bicarbonate
µm	micrometer
PACl	polyaluminum chloride
PWB	Portland Water Bureau
SDS	simulated distribution system
TBD	to be determined
TOC	total organic carbon
TM	technical memorandum
WTP	water treatment plant

1. JAR TEST APPROACH

This Technical Memorandum (TM) summarizes results from the second round of water sampling and jar tests conducted by the Portland Water Bureau (PWB) in March 2019 for the Bull Run Filtration Program. In general, procedures were generally followed according to the test plan (dated February 26, 2019), with some modifications and specifications determined through email communication. Any differences from the recommendations in the testing plan are provided in the text of this document (e.g., if a different dose range was used for a coagulant or polymer).

1.1 Purpose

The purpose of jar testing is to screen the performance of selected water treatment coagulants and polymers used during coagulation, flocculation, and sedimentation. This screening, to be conducted multiple times prior to the start of pilot testing, provides information that will be carried forward into the pilot testing program. The goal of screening these treatment chemicals is to determine dose ranges for primary coagulants (and polymers) that promote particle destabilization (i.e., pre-conditioning for filtration). Selection of coagulants (and polymers) is based on the ability to achieve an acceptable pre-filtration water quality. In general, this acceptance is based upon relatively low recordings for turbidity and filterability index (FI), and additional indicators such as organics. Based on jar results, chemicals will be selected for further performance evaluation during dynamic, pilot testing conditions.

Although determining performance of coagulants is not a primary goal, some performance characteristics may be inferred from jar testing which includes dose ranges for coagulants that may (or may not) remove organic matter. More detailed organics removal and other performance characteristics, such as actual filter run performance and overall reduction in disinfection by-product (DBP) levels, will be evaluated during pilot testing.

1.2 Testing Approach

Testing was conducted by following a phased approach to evaluating coagulants and polymers. The overall testing approach included the following steps:

1. Collect 240-L of raw, Bull Run water using 10-L low-density polyethylene cubitainers;
2. Allow raw water to reach approximately 2-6 °C prior to testing and monitor temperature throughout test, temperature changes noted.
3. Test coagulants without pH adjustment over a range of doses;
4. Test coagulants with alkalinity adjustments specifically when alum and ferric doses warranted the addition of NaHCO_3 and conditions are determined to be alkalinity limited;
5. Test coagulants at six doses with cationic flocculant aid polymers;
6. Document impact of jar testing on turbidity and other indicators, including organic matter surrogates;
7. Perform a filterability index (FI) test to simulate the relative impacts that different chemical dosing strategies may have on filter performance.

Similar to round one, low raw water turbidity brought challenges observing visual differences and analysis of results. In order to mitigate some of these issues, the following changes to the instrumental and procedure were introduced during round 2 of testing:

- A more sensitive turbidimeter was purchased and utilized (Hach TU5300) increasing the accuracy to +/- 0.01 NTU, providing a more sensitive metric.
- The FI test was modified to further standardize the analysis resulting in comparable data. In order for the analyst to recognize the completion of the water filtration, the end was based on the filtrate volume. The FI was also conducted using large funnels with an approximate capacity of 120 mL, 250 mL graduated cylinders, and larger filters (Whatman 18.5 cm diameter) resulting in one pour of 100 mL instead of the multiple pours, as done previously. The filter paper was also consistently rinsed with 25-35 mL of ultrapure water to seat it in the funnel. The graduated cylinders were then emptied after the ultrapure rinse, prior to filtering each sample.
- A vacuum filter apparatus with 47 mm Whatman 0.45 μ filters was used for UV₂₅₄ and color analysis instead of plastic 60 mL syringes with screw on disposable filters used in earlier testing. Approximately 25 mL of sample was filtered to waste, as done previously.
- Settling time for all samples was reduced from 60 minutes to 30 minutes in order to better represent full-scale conditions for sedimentation.

A new challenge faced in the second round of jar testing was the color analysis due to the Hach DR1900 malfunction after phase two. While true and apparent color were still analyzed, the instrument and corresponding method did change. Without the use of the DR1900, PWB's laboratory staff was able to assist and measure true and apparent color according to Standard Method 2120F, using multiple wavelengths with the DR5000 and the jar testing team was able to use a Hach DR900, measuring absorption at 420 nm, but with less consistent results.

Data from a more sensitive turbidity reading, a standardized FI test as well as UV₂₅₄, TOC, and DOC, were all used to compare the relevant coagulant, polymers, and dosages.

1.3 Testing Timeline and Raw Water Characteristics

Attachment A summarizes characteristics of the raw Bull Run water collected from headworks (at 2PIS) for this test. Twenty-four, 10-L cubitainers of water were collected on March 1, 2019 and stored in coolers, at approximately 0-10 °C. Water turbidity was 0.235 NTU, pH 7.05 and temperature 3.8 °C upon collection. Jar testing with this 240-L water sample was conducted across 7 days that spanned March 4 - 15, 2019. Raw water quality was sampled 7 times across the two weeks of testing, with results shown in **Table 1**. TOC was comprised of mostly DOC, though the increased DOC values are believed to be impacted from the filtering process.

Date Measured	pH (units)	Turbidity (NTU)	Apparent Color (units)	True Color ^{a, b} (units)	UV ₂₅₄ (1/cm)	Filtered UV ₂₅₄ (1/cm)	DOC ^c (mg/L)	TOC (mg/L)
20190304	6.9	0.20	10	6	0.039	0.039	0.9	0.9
20190305	7.1	0.26	8	6	0.041	0.040	0.9	0.8
20190307	6.9	0.21	8	8	0.043	0.037	1.0	0.9
20190308	7.2	0.21	9	7	0.063	0.038	1.0	0.8

Table 1. Raw Water Quality								
Date Measured	pH (units)	Turbidity (NTU)	Apparent Color (units)	True Color ^{a, b} (units)	UV ₂₅₄ (1/cm)	Filtered UV ₂₅₄ (1/cm)	DOC ^c (mg/L)	TOC (mg/L)
20190311	6.9	0.18	7	6	0.047	0.038	0.9	0.8
20190314	7.5	0.35	8	7	0.037	0.035	0.8	0.8
20190315	7.1	0.24	8	6	0.038	0.037	0.8	0.8
Average	7.1	0.24	8	6.5	0.044	0.038	0.9	0.8

- Filtered at 0.45 μm , using 47mm Whatman filters and filtering apparatus.
- Instrument, and analysis wavelengths changed after phase 2 due to instrument malfunction.
- In round one, it was noticed that sample filters may have been adding organic carbon in error to DOC samples during some of these first tests (causing DOC > TOC errors). While procedures were changed to allow more of a filter rinse, DOC > TOC was still observed in this round of jar testing.

2. RESULTS

Coagulants tested included aluminum sulfate (alum), ferric chloride (ferric), polyaluminum chloride (PACl, PAX-18), and an aluminum chloralhydrate (ACH, PAX-XL19). After the determination of best coagulant dosages, polymers included polyamine cationic polymer (Clarifloc C-309P) and cationic polydadmec (Clarifloc C-308P) were tested at these optimal coagulant dosages.

2.1 Coagulant-Only Tests

Initial test results (Phase 2) are presented below in **Figure 1**. Note that data exceeding the top of the FeCl_3 graph was plotted in order to (a) keep y-axes similar between graphs, and (b) not focus on 'poor performance' conditions represented by elevated datapoints. An optimal result is expected to occur at the best (low) FI turbidity and (low) FI time combinations.

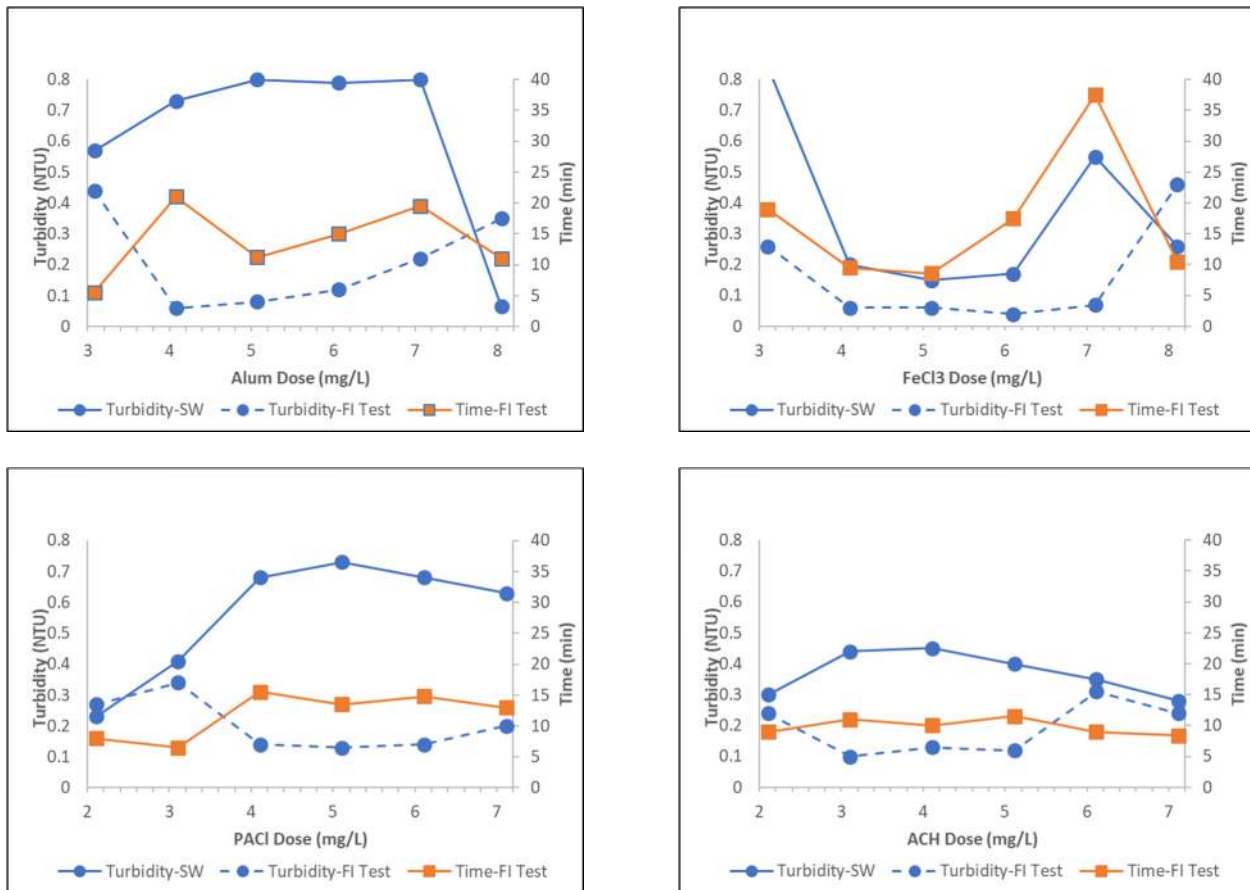


Figure 1. Coagulant-only results for turbidity, before and after FI test, and filterability index time

Results of these tests are summarized as follows:

- Alum showed good performance at 3 to 5 mg/L. While filterability time was also low at 8 mg/L, FI turbidity was greater than settled water turbidity at that dose.
- Ferric performed well at 4 and 5 mg/L. While the FI time was also low at the 8 mg/L dose, the FI filtered turbidity at that dose was higher than the settled water, indicating some sort of filter break through.
- While PACl performed well between 4 mg/L and 7 mg/L with almost a horizontal line of FI times and FI turbidity, 2-3 mg/L dose of PACl was optimal
- ACH showed good performance between 3 and 5 mg/L with both low FI times and good turbidity removal after filtration. ACH also had decent performance at the lowest dose of 2 mg/L as well as the higher doses of 6 and 7 mg/L. Although the low and high ends showed similar FI time, the turbidity differences between the settled water and the FI were almost non-existent.

In addition to turbidity and FI time, removal of organic matter was also assessed. For this round of testing, ultraviolet absorbance at 254nm (UV₂₅₄), and dissolved and total organic carbon (DOC and TOC) were used to measure organics removal. UV₂₅₄ absorbance readings were made before and after filtering through a 0.45 µm filter, TOC was not filtered, while DOC was filtered through a 0.45 µm filter

prior to analysis. Generally, true and apparent color are also used as a surrogate but because of changes in the method of analysis, it will not be used in the evaluation this round.

UV₂₅₄ transmittance results, calculated from the UV absorbance measurements, are shown in **Figure 2**. With the exception of ferric when looking at unfiltered UV₂₅₄ transmittance, all performed similarly, around 90-92%. After filtration, all coagulants performed similar, with a slight increase in transmittance, at approximately 98%. The raw water and day one control sample showed UV₂₅₄ transmittance results at 92% before and after filtration.

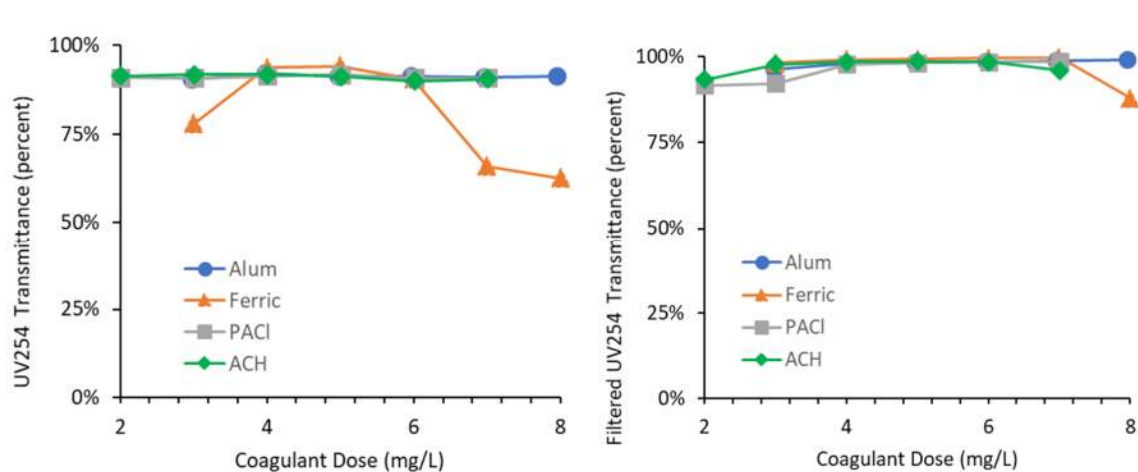


Figure 2. Phase Two - Coagulant-only results for unfiltered and filtered UV transmittance

TOC and DOC for each coagulant are shown below in Error! Reference source not found.. Although DOC concentrations are expected to be lower than TOC concentrations, that was not always seen with these data. There were times when DOC concentrations were higher than TOC concentrations for the same sample. For the raw water quality parameters measured throughout round two jar testing, TOC and DOC ranged from 0.8-0.9 mg/L and 0.8-1.0 mg/L, with averages of 0.8 mg/L and 0.9 mg/L respectively. These data point to introduction of carbon while filtering.

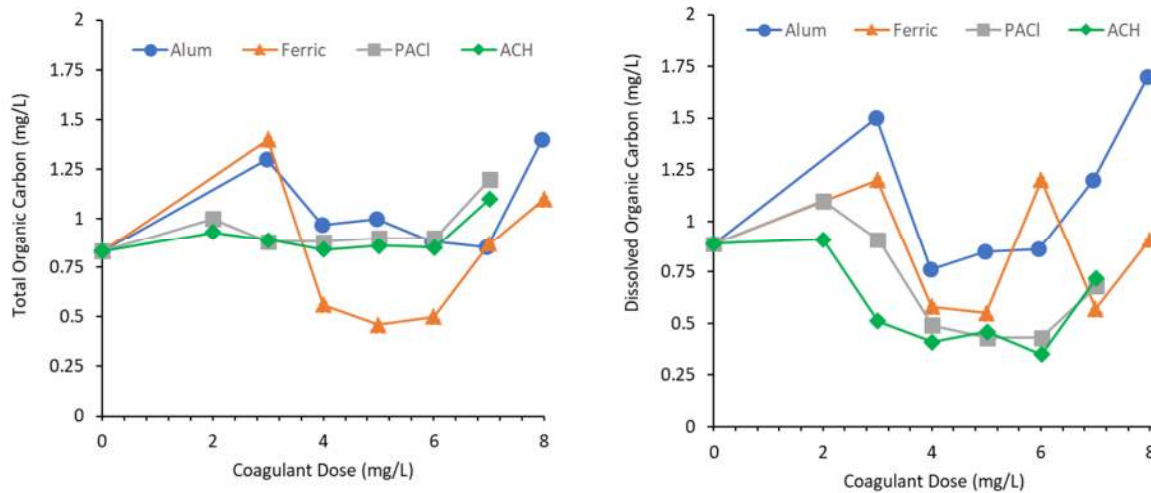


Figure 3. Phase Two - Coagulant-only results for TOC and DOC

- When compared to the average TOC and DOC levels in the raw water, alum did not show much improvement in removal. An alum dose of 4 mg/L showed the most removal of DOC.
- When only looking at the TOC with ferric addition, the mid-range doses of 4-6 mg/L FeCl_3 showed a reduction to approximately 0.5 mg/L respectively. Doses of 4-5 mg/L also showed a reduction in DOC.
- PACl did show a reduction of DOC at mid-range doses of 4-6 mg/L.
- The TOC and DOC concentrations were fairly consistent across ACH doses, with a slight increase in at 7 mg/L of ACH. DOC did show lower concentrations at the ACH doses of 3-6 mg/L, with both the 2 mg/L and the 7 mg/L at higher concentrations.

All coagulants were analyzed further at 3.0 mg/L and 5.0 mg/L with the addition of 0.5 and 1.0 mg/L of polymers in the remaining phases. Alum, PACl, ferric, and ACH were tested at the chosen dosages with polymers based on the following results:

- All coagulants showed good particle removal and FI time at medium dosages.
- All of the coagulants at low to mid dosages, with the exception of ferric at 3 mg/L, showed UV_{254} absorbances below the raw water average and a reduction in absorbance when filtered.
- PACl and ACH showed consistent DOC removal at 4 and 5 mg/L and ferric showed good DOC and TOC removal at the same dosages.

2.2 Flocculant-Aid Polymer Tests

After coagulant dose range was narrowed down from the results of the previous phase, the impact of polymer addition was tested. In **Figure 4**, the turbidity removal and FI times are shown for all coagulants and Clarifloc C-308P addition. All polymers were added at the beginning of the flocculation stage, immediately after rapid mixing was completed. As mentioned above, both Clarifloc polymers were added at 0.5 and 1.0 mg/L. **Figure 5** portrays similar data with the alternative polymer tested, Clarifloc C-309P.

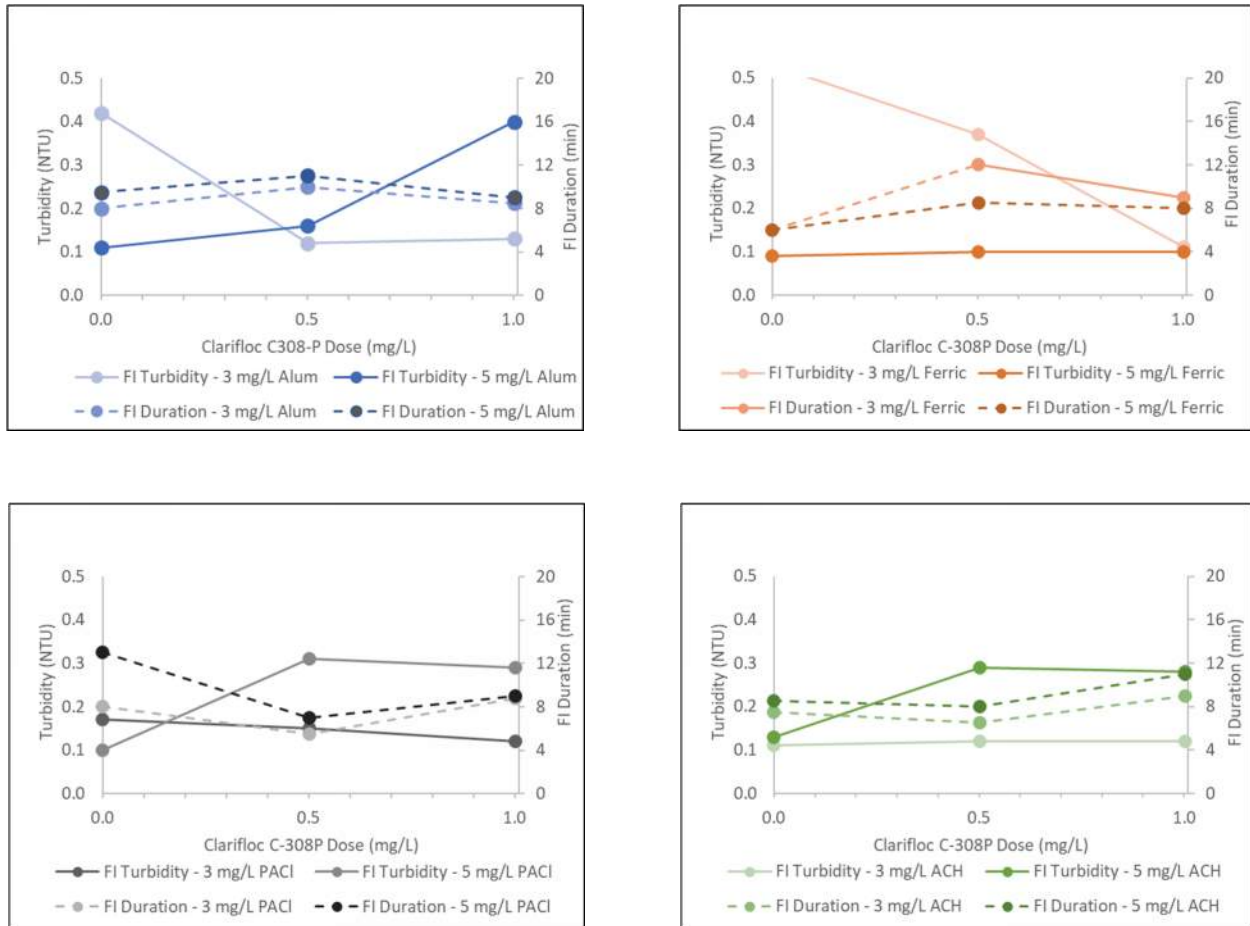


Figure 3. Turbidity and filterability index time results with Clarifloc C-308P

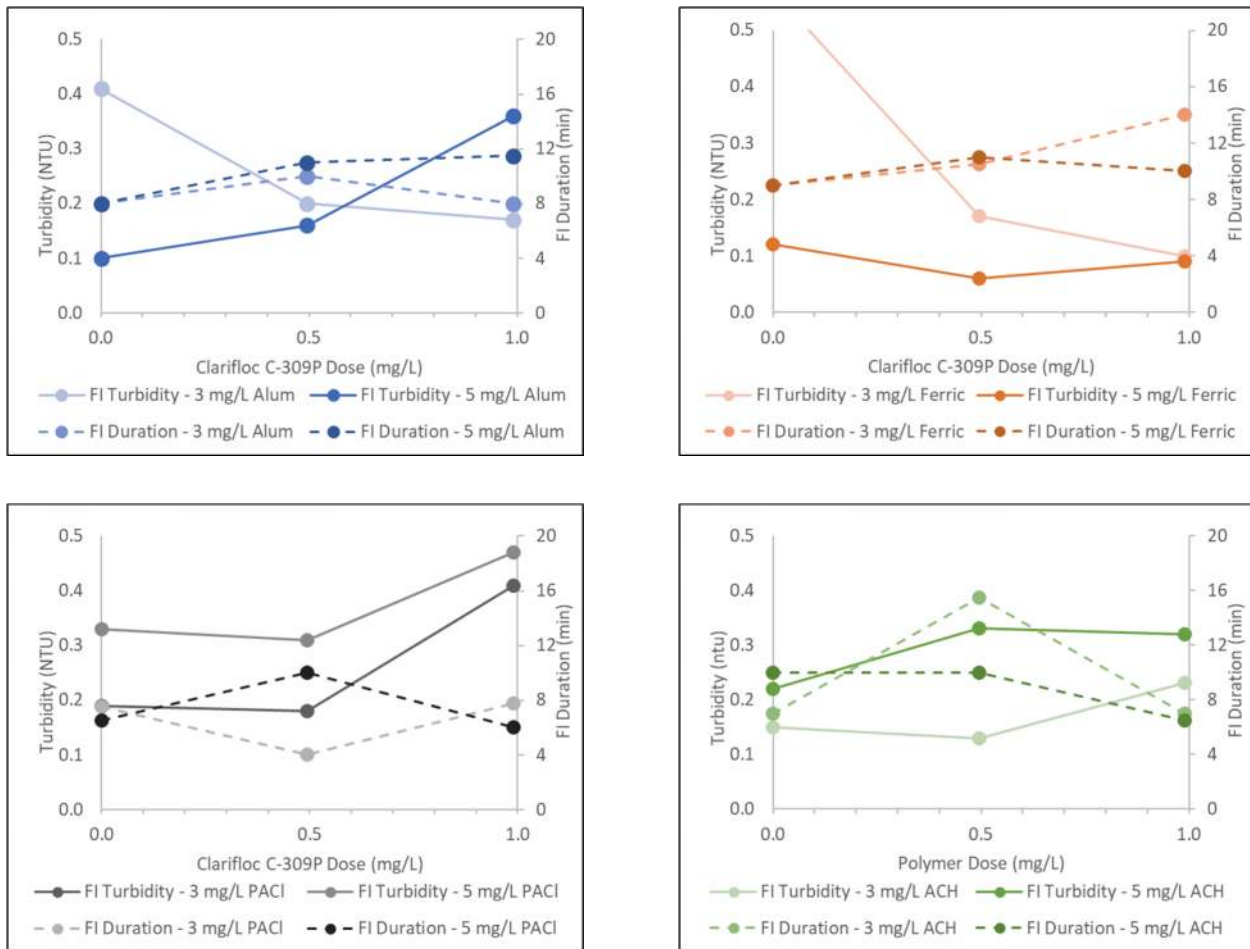


Figure 5. Turbidity and filterability index time results with Clarifloc C-309P

The addition of both polymers resulted in differing outcomes for FI time and turbidity, dependent on the coagulant, polymer, and dose for both. In some cases, the addition of a polymer resulted in higher turbidity and longer FI test times. For example, this trend was seen with the FI test times increasing when both Clarifloc C=308P and C=309P were added with ferric. This was matched with a decrease in turbidity, however.

In other cases, turbidity increased significantly in higher coagulant dosages paired with higher polymer dosages. This probable filter breakthrough was seen in the 5 mg/L alum run when combined with both polymers as well as both PACI dosages when combined with 1.0 mg/L Clarifloc C-309P.

When comparing FI tests and turbidity changes, it is difficult to determine that one performed better than the other, with inconsistent results or variations between tests. It does seem that low doses of polymers improve turbidity, when in combination with 3 mg/L of coagulant. When polymers are added to 5 mg/L of coagulant, the turbidity and FI test time increases.

Beyond turbidity and FI tests, polymer dose impacts on DOC reduction are shown in Error! Reference source not found..

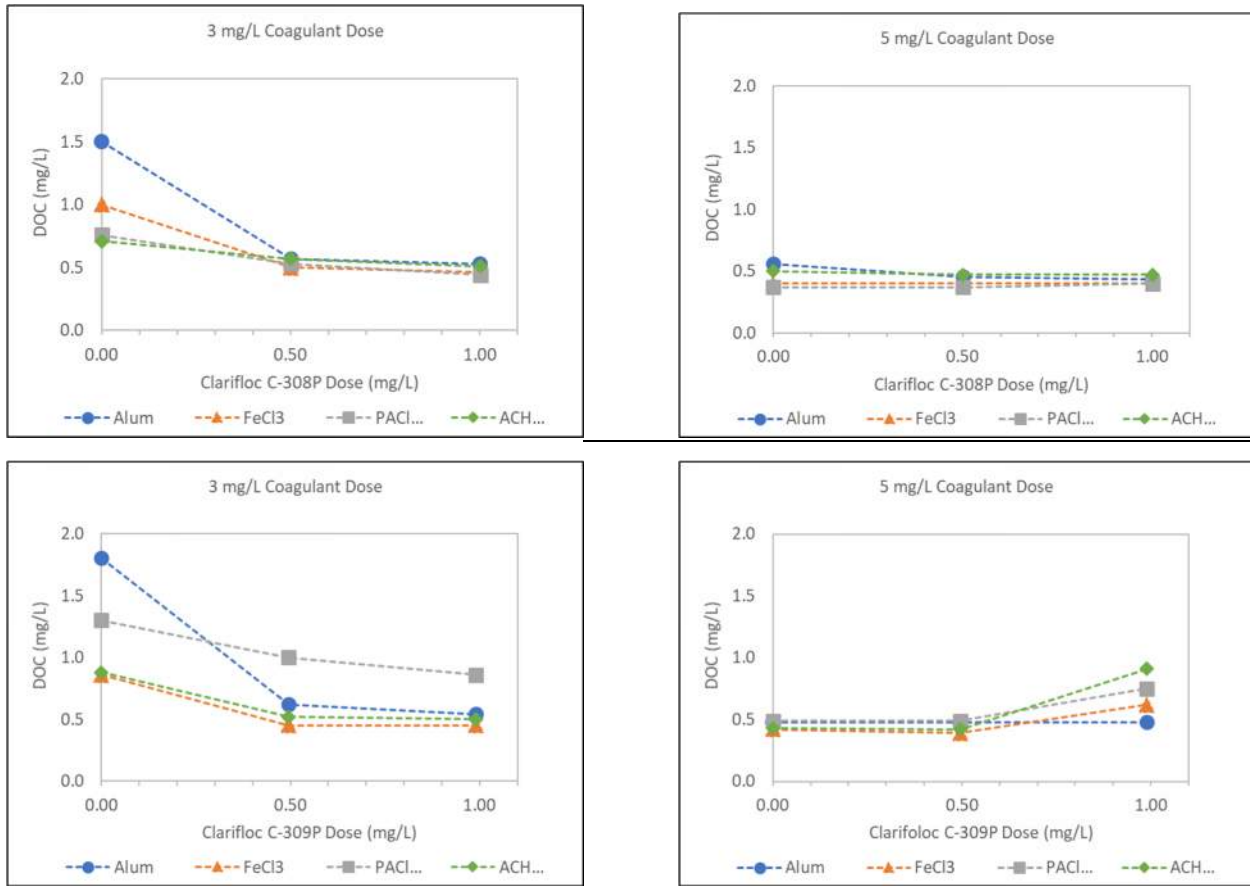


Figure 6. DOC results with Clarifloc C-308P and C-309P

While all of the polymer dosages showed improvement in DOC removal with coagulants at 3 mg/L, the addition of 1.0 mg/L of Clarifloc C-309P at 5 mg/L coagulant showed an increase in DOC concentrations for ferric, PACl, and ACH. Clarifloc C-308P showed the greatest benefit at a low polymer dose (0.5 mg/L) when coagulants were also dosed at 3 mg/L.

Result interpretation did prove difficult as raw water quality DOC across the days tested was averaged at 0.9 mg/L DOC with a great deal of coagulant only jars, exceeding this amount.

3. SUMMARY

This second round of testing has continued to produce a great deal of useful data. Although visual floc is difficult to obtain, results are showing that low coagulant doses have positive results when considering the filterability, decreasing turbidity, and minimizing organic matter. These low coagulant doses, with the addition of low polymers doses offer potential for pilot testing.

For assessing the coagulant-only tests, the following results were observed.

- All coagulants performed well with respect to FI time and turbidity at dosages ranging from 3 mg/L through 5 mg/L, depending on the coagulant.
- There continued to be some discrepancies between TOC and DOC data, potentially due to the filtering process.

- DOC had significant removal, at times a 40-60% reduction, when primary coagulants were dosed at 5 mg/L.

For the flocculant aid testing, the following results were observed:

- The addition of both polymers resulted in differing outcomes for FI time and turbidity, dependent on the coagulant, polymer, and dose for both. In some cases, the addition of a polymer resulted in higher turbidity and longer FI test times. It does seem that low doses of polymers improve turbidity, when in combination with 3 mg/L of coagulant. When polymers are added to 5 mg/L of coagulant, the turbidity and FI test time increases.
- When Clarifloc C-308P and C-309P were used in combination with lower coagulants dosages such as 3 mg/L, additional organics and color removal was observed.

Attachment A: Raw Data

Bull Run Water Jar Testing Results: Round 2

Phase	Chemical	Coag Dose (mg/L)	Bicarb Dose (mg/L)	Polymer Dose (mg/L)	Raw or Settled Water												FI Test		
					Floc Start Temp (degC)	SW Temp (degC)	pH	Alk (mg/L-CaCO3)	Turb (ntu)	Color, App	Color, True	UV254	UV254 (0.45um)	UVT (0.45um)	DOC (mg/L)	TOC (mg/L)	Turb (ntu)	FI	Time (min)
Raw Water	Day 1						6.9	7.6	0.20	10	6	0.039	0.039	91%	0.9	0.9			
	Day 2						7.1	7.8	0.26	8	6	0.041	0.040	91%	0.9	0.8	0.06		4
	Day 3						6.9	8.6	0.21	8	8	0.043	0.037	92%	1.0	0.9	0.04		4.75
	Day 4						7.2	7.8	0.21	9	7	0.063	0.038	92%	1.0	0.8	0.05		3
	Day 5						6.9	7.4	0.18	7	6	0.047	0.038	92%	0.9	0.8			
	Day 6						7.5	8.1	0.35	8	7	0.037	0.035	92%	0.8	0.8	0.06		4
	Day 7						7.1	7.4	0.24	8	6	0.038	0.037	92%	0.8	0.8			
Phase 1 (bicarb added to target min pH ~6.0 and min alk ~6 mg/L-CaCO3)	Alum	0	0		5.0	12.0	7.2	8.1	0.20	7	4	0.040	0.037	92%	1.2	1.1	0.20	1.3	5
		3	0		4.9	10.6	7.0	6.6	0.59	10	4	0.042	0.019	96%	0.6	0.9	0.42	2.4	10
		6	3		5.0	11.3	6.8	6.2	0.81	13	0	0.042	0.011	97%	0.5	0.9	0.20	2.3	9
		10	7		5.0	11.3	6.6	5.2	0.58	10	3	0.042	0.018	96%	0.5	0.9	0.40	2.8	11
		15	16		5.0	11.7	6.5	6.0	0.47	10	0	0.041	0.004	99%	0.5	0.9	0.37	5.3	21
		20	25		5.2	12.2	6.2	6.2	0.48	9	4	0.040	0.006	99%	0.5	0.9	0.50	2.6	10
	Ferric Chloride	0	0		5.2	12.4	6.9	7.7	0.20	9	3	0.036	0.038	92%	1.2	1.2	0.22	1.6	7
		3	6		5.2	12.0	6.8	6.6	0.64	23	4	0.108	0.013	97%	0.9	1.1	0.53	5.5	22
		6	12		5.2	12.1	6.6	5.6	0.16	6	0	0.026	0.004	99%	0.5	0.6	0.07	4.5	18
		9	18		5.1	12.1	6.3	5.4	0.13	8	0	0.030	0.003	99%	0.5	0.6	0.10	2.9	12
		12	24		5.3	12.5	6.1	4.1	0.27	24	0	0.103	0.004	99%	0.5	0.8	0.05	5.0	20
		15	32		5.6	12.7	6.0	3.8	0.82	65	0	0.257	0.003	99%	0.5	1.0	0.10	5.5	22
	PACl (PAX-18)	2	0		4.6	11.0	6.8	7.8	0.26	8	6	0.038	0.033	93%	1.1	1.1	0.20	1.5	6
		3	0		4.4	10.5	6.9	7.1	0.63	11	1	0.040	0.011	97%	0.5	0.9	0.25	1.8	7
		6	0		4.3	10.8	6.5	6.6	0.73	11	1	0.039	0.012	97%	0.4	0.9	0.18	1.9	8
		10	0		4.4	11.8	6.6	5.3	0.31	9	3	0.037	0.007	98%	0.8	0.9	0.38	2.0	8
		15	0		4.3	11.9	6.5	4.5	0.32	9	6	0.038	0.034	92%	0.9	0.9	0.23	1.8	7
		20	0		4.1	12.1	6.1	2.8	0.28	9	8	0.037	0.033	93%	0.9	0.9	0.21	1.8	7
	ACH (PAX-XL19)	0	0		2.0	9.9	7.3	7.7	0.23	7	6	0.038	0.040	91%	1.2	1.1	0.16	2.6	11
		3	0		2.1	8.8	7.2	7.7	0.49	9	2	0.038	0.014	97%	0.5	0.9	0.15	4.6	19
		6	0		2.1	9.6	7.1	7.6	0.33	9	1	0.040	0.027	94%	0.7	0.9	0.26	3.4	14
		10	0		2.1	9.6	7.1	7.5	0.25	10	6	0.040	0.035	92%	0.9	0.9	0.21	2.8	11
		15	0		2.1	10.1	6.9	7.2	0.28	9	7	0.042	0.038	92%	0.8	0.9	0.21	3.0	12
		20	0		0.9	11.9	6.2	5.8	0.57	10	3	0.043	0.016	96%	1.5	1.3	0.44	1.4	6
Phase 2 (no alkalinity/pH adjustment performed)	Alum	4	0		6.4	10.7	7.2	6.0	0.73	11	2	0.036	0.009	98%	0.8	1.0	0.06	5.3	21
		5	0		6.6	11.5	7.0	5.5	0.80	11	1	0.040	0.008	98%	0.9	1.0	0.08	2.8	11
		6	0		6.4	11.3	6.8	5.3	0.79	12	1	0.040	0.006	99%	0.9	0.9	0.12	3.8	15
		7	0		6.3	10.8	6.7	4.3	0.80	11	1	0.041	0.005	99%	1.2	0.9	0.22	4.9	20
		8	0		6.5	12.2	6.6	4.5	0.07	11	2	0.040	0.004	99%	1.7	1.4	0.35	2.8	11
		8	0		6.3	12.4	6.6	4.3	0.84	28	2	0.108	0.008	98%	1.2	1.4	0.26	4.8	19
	Ferric Chloride	4	0		6.2	12.0	6.4	4.6	0.20	9	2	0.028	0.004	99%	0.6	0.6	0.06	2.4	10
		5	0		6.2	12.0	6.3	3.5	0.15	8	2	0.026	0.003	99%	0.6	0.5	0.06	2.2	9
		6	0		6.1	12.4	6.2	2.2	0.17	12	1	0.043	0.002	100%	1.2	0.5	0.04	4.4	18
		7	0		6.2	12.4	5.9	1.3	0.55	30	1	0.181	0.001	100%	0.6	0.9	0.07	9.4	38
		8	0		6.3	13.0	5.4	0.8	0.26	47	14	0.204	0.056	88%	0.9	1.1	0.46	2.6	11
		8	0		6.3	13.0	5.4	0.8	0.26	47	14	0.204	0.056	88%	0.9	1.1	0.46	2.6	11
	PACl (PAX-18)	2	0		5.2	12.1	7.1	7.5	0.23	9	7	0.041	0.038	92%	1.1	1.0	0.27	2.0	8
		3	0		5.0	11.2	7.0	7.4	0.41	10	6	0.042	0.035	92%	0.9	0.9	0.34	1.6	7
		4	0		5.5	11.9	7.0	7.0	0.68	11	3	0.039	0.010	98%	0.5	0.9	0.14	3.9	16
		5	0		4.9	12.0	6.9	6.5	0.73	11	1	0.037	0.008	98%	0.4	0.9	0.13	3.4	14
		6	0		5.3	12.4	6.9	6.9	0.68	11	2	0.042	0.007	98%	0.4	0.9	0.14	3.7	15
		7	0		5.6	13.2	6.9	6.0	0.63	11	1	0.042	0.006	99%	0.7	1.2	0.20	3.3	13
	ACH (PAX-XL19)	2	0		5.9	11.9	7.3	7.1	0.30	9	6	0.039	0.030	93%	0.9	0.9	0.24	2.3	9
		3	0		5.9	11.3	7.2	7.8	0.44	10	2	0.037	0.010	98%	0.5	0.9	0.10	2.8	11
		4	0		5.8	12.2	7.2	7.8	0.45	10	1	0.037	0.007	98%	0.4	0.8	0.13	2.5	10
		5	0		5.8	11.9	7.2	7.6	0.40	10	2	0.040	0.006	99%	0.5	0.9	0.12	2.9	12
		6	0		5.8	12.4	7.1	7.6	0.35	10	1	0.046	0.007	98%	0.4	0.9	0.31	2.3	9
		7	0		5.7	13.0	7.1	7.5	0.28	10	4	0.043	0.018	96%	0.7	1.1	0.24	2.1	8

Bull Run Water Jar Testing Results: Round 2

Phase 3a (Primary Coagulants dosed at 3 and 5 mg/L with cationic polymer polydadmac Clarifloc 308P dosed at 0, 0.5, and 1.0 mg/L)	Alum	3	0	0.0	7.1	12.5	7.1	6.5	0.52	9	2	0.043	0.020	95%	1.5	1.5	0.42	2.0	8
		3	0	0.5	7.1	11.8	7.0	6.3	0.61	10	0	0.039	0.011	97%	0.6	0.9	0.12	2.5	10
		3	0	1.0	7.1	12.2	6.9	6.6	0.61	9	1	0.038	0.010	98%	0.5	0.8	0.13	2.1	9
		5	0	0.0	7.0	12.4	6.8	5.8	0.82	11	1	0.041	0.008	98%	0.6	1.0	0.11	2.4	10
		5	0	0.5	7.0	12.9	6.7	5.4	0.74	10	0	0.043	0.008	98%	0.5	0.8	0.16	2.8	11
		5	0	1.0	6.9	12.9	6.7	5.7	0.67	10	1	0.044	0.007	98%	0.4	0.9	0.40	2.3	9
	Ferric Chloride	3	0	0.0	6.7	10.6	6.7	5.6	0.62	23	14	0.103	0.067	86%	1.0	1.2	0.53	1.5	6
		3	0	0.5	6.7	11.2	6.7	5.5	0.83	25	1	0.098	0.012	97%	0.5	0.8	0.37	3.0	12
		3	0	1.0	6.6	11.5	6.6	5.1	0.63	17	1	0.050	0.009	98%	0.5	0.8	0.11	2.3	9
		5	0	0.0	6.5	12.0	6.4	4.3	0.27	8	1	0.029	0.007	98%	0.4	0.6	0.09	1.5	6
		5	0	0.5	6.4	12.0	6.4	3.7	0.27	10	2	0.051	0.006	99%	0.4	0.6	0.10	2.1	9
		5	0	1.0	6.3	12.3	6.4	3.9	0.46	17	1	0.052	0.007	98%	0.4	0.7	0.10	2.0	8
	PACI (PAX-18)	3	0	0.0	6.9	12.0	6.9	7.3	0.42	9	2	0.039	0.013	97%	0.8	1.1	0.17	2.0	8
		3	0	0.5	7.2	12.1	6.8	7.7	0.45	9	2	0.037	0.009	98%	0.5	0.9	0.15	1.4	6
		3	0	1.0	7.3	11.6	6.8	7.0	0.49	9	1	0.040	0.009	98%	0.4	0.8	0.12	2.2	9
		5	0	0.0	6.9	11.7	6.7	7.2	0.41	10	1	0.041	0.007	98%	0.4	0.8	0.10	3.3	13
		5	0	0.5	6.8	11.2	6.8	7.4	0.41	9	1	0.043	0.007	98%	0.4	0.8	0.31	1.8	7
		5	0	1.0	6.9	11.6	6.7	7.3	0.33	9	2	0.042	0.010	98%	0.4	0.8	0.29	2.3	9
	ACH (PAX-XL19)	3	0	0.0	7.6	13.0	7.2	7.4	0.50	9	2	0.036	0.010	98%	0.7	1.0	0.11	1.9	8
		3	0	0.5	7.5	12.6	7.2	7.5	0.49	10	1	0.035	0.008	98%	0.6	0.9	0.12	1.6	7
		3	0	1.0	7.5	12.2	7.1	7.3	0.67	10	1	0.038	0.007	98%	0.5	0.8	0.12	2.3	9
		5	0	0.0	7.5	12.8	7.1	8.4	0.54	10	1	0.039	0.005	99%	0.5	0.9	0.13	2.1	9
		5	0	0.5	7.5	12.4	7.0	7.2	0.89	9	1	0.040	0.004	99%	0.5	0.9	0.29	2.0	8
		5	0	1.0	7.4	12.9	7.0	7.9	0.36	9	0	0.040	0.005	99%	0.5	0.9	0.28	2.8	11
Phase 3b (Primary Coagulants dosed at 3 and 5 mg/L with cationic polymer polyamine Clarifloc 309P dosed at 0, 0.5, and 1.0 mg/L)	Alum	3	0	0.0	6.8	12.6	7.0	6.6	0.48	9	4	0.041	0.021	95%	1.8	2.0	0.41	2.0	8
		3	0	0.5	6.8	11.9	6.7	6.8	0.60	11	2	0.038	0.011	97%	0.6	0.9	0.20	2.5	10
		3	0	1.0	6.8	11.8	6.9	6.2	0.61	10	1	0.037	0.008	98%	0.5	0.9	0.17	2.0	8
		5	0	0.0	6.7	12.4	6.7	5.5	0.80	11	1	0.039	0.008	98%	0.5	0.9	0.10	2.0	8
		5	0	0.5	6.6	12.3	6.6	5.5	0.71	10	1	0.042	0.006	99%	0.5	0.9	0.16	2.8	11
		5	0	1.0	6.7	12.8	6.7	5.1	0.82	11	1	0.042	0.007	98%	0.5	0.9	0.36	2.9	12
	Ferric Chloride	3	0	0.0	6.3	12.3	6.7	5.8	0.63	24	12	0.099	0.053	89%	0.9	1.0	0.57	2.3	9
		3	0	0.5	6.3	12.0	6.6	5.2	0.69	18	2	0.058	0.007	98%	0.5	0.8	0.17	2.6	11
		3	0	1.0	6.3	12.4	6.6	3.2	0.70	20	1	0.049	0.006	99%	0.5	0.8	0.10	3.5	14
		5	0	0.0	6.5	12.0	6.4	3.9	0.23	10	1	0.029	0.004	99%	0.4	0.6	0.12	2.3	9
		5	0	0.5	6.5	11.9	6.4	3.7	0.30	14	1	0.041	0.004	99%	0.4	0.6	0.06	2.8	11
		5	0	1.0	6.5	12.1	6.3	3.7	0.90	32	1	0.112	0.004	99%	0.6	1.0	0.09	2.5	10
	PACI (PAX-18)	3	0	0.0	7.0	13.0	7.1	6.8	0.21	7	6	0.039	0.037	92%	1.3	1.2	0.19	1.9	8
		3	0	0.5	7.0	13.6	7.1	7.4	0.28	8	6	0.038	0.037	92%	1.0	0.9	0.18	1.0	4
		3	0	1.0	7.0	13.5	7.1	7.1	0.51	9	6	0.040	0.031	93%	0.9	0.9	0.41	1.9	8
		5	0	0.0	6.9	14.1	7.1	6.7	1.17	11	1	0.038	0.007	98%	0.5	0.9	0.33	1.6	7
		5	0	0.5	6.9	14.1	7.0	6.1	0.74	11	1	0.041	0.007	98%	0.5	0.9	0.31	2.5	10
		5	0	1.0	6.9	14.6	6.9	6.1	0.77	11	1	0.043	0.006	99%	0.8	1.1	0.47	1.5	6
	ACH (PAX-XL19)	3	0	0.0	7.0	12.5	7.1	7.6	0.53	9	1	0.037	0.009	98%	0.9	1.2	0.15	1.8	7
		3	0	0.5	6.9	12.8	7.1	7.9	0.93	9	1	0.038	0.009	98%	0.5	0.9	0.13	3.9	16
		3	0	1.0	6.9	13.3	6.9	7.3	0.57	9	2	0.040	0.008	98%	0.5	0.8	0.23	1.8	7
		5	0	0.0	7.0	13.9	7.0	7.0	0.55	10	1	0.040	0.006	99%	0.4	0.9	0.22	2.5	10
		5	0	0.5	6.9	13.3	6.9	7.8	0.70	10	1	0.041	0.006	99%	0.4	0.8	0.33	2.5	10
		5	0	1.0	7.0	14.7	7.0	8.2	0.68	10	1	0.041	0.005	99%	0.9	1.4	0.32	1.6	7



Technical Memorandum

Subject: Bull Run Water Jar Testing Results Round 3 (April 2019)

PWB Project: 30006570

BC Project: 152606

Date: July 19, 2019

Revised: March 10, 2019

To: Yone Akagi, Water Quality Manager

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CONTENTS

1. Background	3
1.1 Purpose	3
1.2 Approach	3
1.3 Timeline and Raw Water Characteristics	4
2. Results.....	4
2.1 Coagulant-Only Tests	4
2.2 Flocculant-Aid Polymer Tests	7
3. Summary and Recommendations.....	8
Attachment A: Raw Data	A-1

List of Figures

Figure 1. Coagulant-only results for turbidity and filterability index (FI) time.....	5
Figure 2. Coagulant-only results for organics reduction	6
Figure 3. Performance of ferric and ACH assisted by polyamine Clarifloc C359 during flocculation.....	7

List of Tables

Table 1. Raw Water Quality.....	4
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List of Abbreviations

2PIS	Second primary intake structure
ACH	aluminum chlorohydrate
alum	aluminum sulfate
BC	Brown and Caldwell
BRFP	Bull Run Filtration Project
CaCO ₃	calcium carbonate
Confluence	Confluence Engineering Group LLC
°C	degrees centigrade
DOC	dissolved organic carbon
FI	filterability index
gpd	gallons per day
gph	gallons per hours
L	liter
lf	linear feet
mgd	million gallons per day
mg/L	milligrams per liter
NaHCO ₃	sodium bicarbonate
µm	micrometer
PACl	polyaluminum chloride
PWB	Portland Water Bureau
TBD	to be determined
TOC	total organic carbon
TM	technical memorandum
WTP	water treatment plant

1. BACKGROUND

This Technical Memorandum (TM) summarizes results from the third round of water sampling and jar tests conducted by the Portland Water Bureau (PWB) in April 2019 for the Bull Run Filtration Program. In general, procedures were followed according to the test plan (dated January 25, 2019) with some modifications that were later implemented during the second round of testing completed in February. Differences from the recommendations in the testing plan are summarized in this document.

1.1 Purpose

This is the final round of jar testing to be conducted prior to the start of pilot testing. The purpose of jar testing is to screen the performance of selected water treatment coagulants and polymers used during coagulation, flocculation, and sedimentation. This screening, to be conducted multiple times prior to the start of pilot testing, provides information that will be carried forward into the pilot testing program. The goal of screening these treatment chemicals is to determine dose ranges for primary coagulants (and polymers) that promote particle destabilization (i.e., pre-conditioning for filtration). Selection of coagulants (and polymers) is based on the ability to achieve an acceptable pre-filtration water quality, but it should be kept in mind that – for low-turbidity conditions such as the Bull Run – it is normal that settled water condition may seem ‘poorer’ (i.e., increased turbidity) due to addition of coagulant. This condition is incorporated into data interpretation for turbidity and filterability index (FI), and additional indicators such as organics. Based on jar results, chemicals will be selected for further performance evaluation during dynamic, pilot testing conditions.

Although determining performance of coagulants is not a primary goal, some performance characteristics may be inferred from jar testing which includes dose ranges for coagulants that may (or may not) remove organic matter. More detailed organics removal and other performance characteristics, such as actual filter run performance and overall reduction in disinfection by-product (DBP) levels, will be evaluated during pilot testing.

1.2 Approach

Testing was conducted by following a phased approach to evaluating coagulants and polymers. The overall testing approach (details provided in previous TMs summarizing round 1 and 2 jar tests) included the following steps:

1. Collect 200-L of raw, Bull Run water using 10-L low-density polyethylene cubitainers;
2. Allow raw water to acclimate to between 11 to 18 °C prior to (and during) testing;
3. Adjust alkalinity of all raw water for conditions that were determined to be alkalinity limited (same as during Round 2 testing);
4. Adjustment of pH was not conducted (interpretation of comparative results should keep this in mind if a coagulant is being applied outside of peak pH conditions);
5. Test aluminum sulfate (alum), ferric chloride (ferric), polyaluminum chloride (PACl) and aluminum chlorohydrate (ACH) at six doses each without flocculant aid, and choose a select group and dose range of coagulants to test with a polyamine cationic polymer (Clarifloc C359, used at the Tacoma Water Green River Filtration Plant) as a flocculant aid;

6. Document impact of jar testing on turbidity and other indicators, including organic matter surrogates; and,
7. Perform FI test (using conditions described for Round 2 tests) to simulate the relative impacts that different chemical dosing strategies may have on filter performance.

1.3 Timeline and Raw Water Characteristics

Raw Bull Run water was collected on April 9 from the south fork tributary for this test in twenty-four, 10-L cubitainers (**Appendix A**). Water was stored on ice outside (ice changed daily) until testing was conducted from April 23rd through 25th. Raw water turbidity was approximately 2 NTU at the time of collection. To represent reservoir-storage effects prior to each test, water was mixed and then allowed to settle for a 1-hour period, then poured off and used in the jar tests. This settled water turbidity ranged from 0.6 to 0.8 NTU. Jar testing was conducted across 3 days at the end of April 2019. Raw water quality was sampled during testing, with results shown in **Table 1**.

Day Measured	pH (units)	Alkalinity (mg/L as CaCO ₃)	Turbidity (NTU)	Apparent Color (units)	True Color ^a (units)	UV ₂₅₄ ^a (1/cm)	DOC ^a (mg/L)	TOC (mg/L)
Apr 23	6.5	5.6	0.84	23	13	0.087	2.2	2.3
Apr 24	6.8	5.2	0.56	22	14	0.088	1.7	1.7
Apr 25	Not analyzed							

a. Filtered at 0.45 µm

2. RESULTS

All test data are provided in **Appendix B**. Test results are summarized below with regard to performance by coagulant only, and coagulant with polymer. Performance is also characterized for each coagulant with regards to turbidity/filterability as well as organics reduction. No pH conditions were controlled during this testing, except for the impact that sodium bicarbonate had when added for the elevated alum, ferric, and PACl tests. As a result, alum pH conditions ranged from 5.8 units (for the greatest alum dose) to 6.6 units (for the lowest alum dose), ferric test pH conditions ranged from 6.1 to 6.4 units, PACl pH conditions ranged from 6.4 to 6.6 units, and ACH pH conditions ranged from 6.6 to 6.8 units. Tests dosing greater than 6 mg/L alum experienced very low alkalinity, ranging from 1.7 to 3.0 mg/L as CaCO₃, possibly negatively-impacting alum performance. All resulting ferric, PACl, and ACH test conditions were conducted at greater than 5 mg/L alkalinity as CaCO₃.

2.1 Coagulant-Only Tests

Figure 1 (all graphs have similar x and y axes) illustrates turbidity and FI time results from coagulant-only conditions with alum, ferric, PACl, and ACH. By reviewing results for turbidity and potential filterability (i.e., lower FI times indicating relatively better filtration potential), the following results are noted:

- Alum showed good performance at 3 mg/L, and although had greater settled and FI turbidities at 6 mg/L, the FI time remained low. FI turbidity dropped at the 9 mg/L, but FI time was much greater. Therefore, it could be argued that alum less than 6 mg/L may be the optimal condition.

- Ferric seemed to show the best settled and FI turbidities at elevated doses (> 10 mg/L, possibly a sweep-floc condition), but filter time seemed best at 3 and 15 mg/L. Therefore, similarly to alum, an optimal ferric dose for maintaining filter performance is likely to be less than 6 mg/L.
- PACI showed best turbidity performance at 3 mg/L (which had a somewhat elevated FI time) and the best FI time and FI turbidity at 9 mg/L. Because FI turbidity spiked at 6 mg/L, the optimal conditions for PACI may be either at 3 or 9 mg/L.
- ACH settled water turbidity levels were best after low doses (less than 6 mg/L); FI turbidity was fairly constant across all doses, but lowest at 9 mg/L. Similar to ferric, FI time was best at the low and high doses. As a result, optimal conditions for ACH may be between 3 to 6 mg/L.

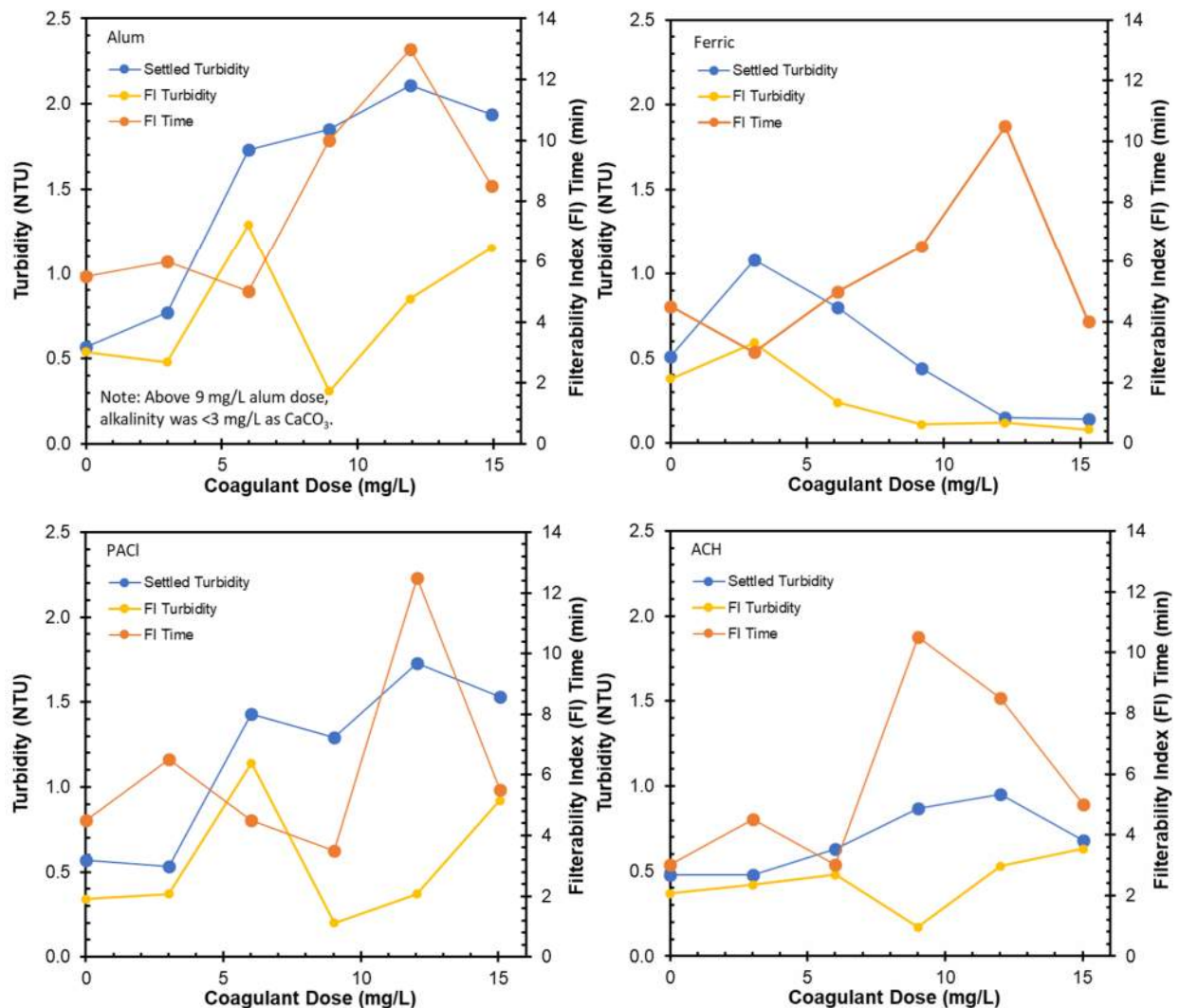


Figure 1. Coagulant-only results for turbidity and filterability index (FI) time

Results showing (clockwise from upper-left) alum, ferric, ACH, and PACI settled water turbidity and FI time

Based on these results, optimal filtration during most turbidity/organics conditions (<2 NTU) is expected to be achieved at low doses for all the tested coagulants. Although the lowest dose of coagulant for these tests was 3 mg/L, it is possible that even lower doses (i.e., less than 3 mg/L) are feasible (and preferable) during pilot-scale testing, especially when source water turbidity is low. This information does not take into account any potential for organics removal (which are described below).

Figure 2 summarizes organics reduction for all coagulants after settling. Note that all parameters, except TOC, were analyzed after processing through a 0.45- μ m filter. Alum and ferric showed excellent performance at doses as low as 6 mg/L. A dose of 6 mg/L provided 85% color removal and 67% DOC removal for alum, and 92% color removal and 73% DOC removal for ferric. UV transmittance, calculated from UV absorbance data, provides better insight into characterizing coagulation performance when compared to graphing absorbance data. Increased UV₂₅₄ transmittance is shown to be an excellent surrogate for organics removal, showing nearly identical improvements when compared to true color and DOC removal for each step-dose condition.

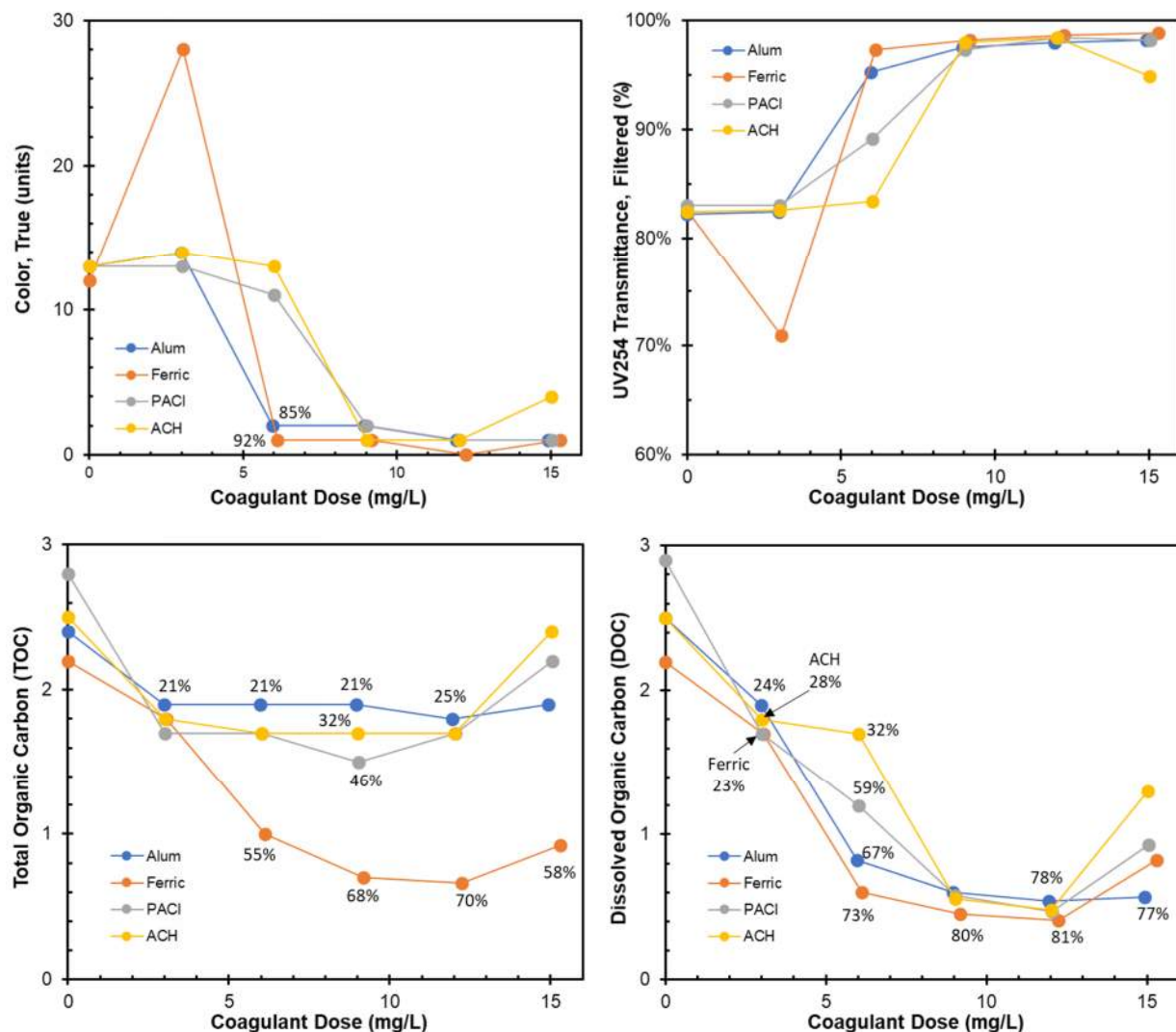


Figure 2. Coagulant-only results for organics reduction

Top: Removal of color and increased UV transmittance at 254 nm (both filtered at 0.45 μ m)

Bottom: Removal of both TOC and DOC (some percent removal data indicated)

TOC results (unfiltered samples), show that settling alone removes at least 20% TOC at a dose as low as 3 mg/L for all coagulants. The overall efficiency of organics removal, for all coagulants, remained somewhat stable or improved in doses up through the 12 mg/L dose, with diminishing returns at 15 mg/L.

2.2 Flocculant-Aid Polymer Tests

Performance of ferric and ACH was evaluated further at two coagulant doses by adding polyamine cationic polymer Clarifloc C359 at the onset of flocculation. A mid-range dose of each coagulant was tested (4 and 7 mg/L ferric, 6 and 9 mg/L ACH) along with two polymer doses (0.3 and 0.6 mg/L) to assess turbidity and organics removal.

Figure 3 summarizes polymer test results. It is unclear if polymer addition actually assisted in turbidity removal (or FI performance) when compared to the coagulant-only condition because FI time generally remained similar or increased with polymer, and turbidity generally remained similar or increased with polymer. Although the 7 mg/L ferric condition seems to have greatly reduced the turbidity level from the 0 mg/L poly condition, it should be however noted that untreated turbidity was 0.6 NTU (i.e., for the 0 mg/L poly condition, turbidity increased from 0.6 to 1.9 NTU).

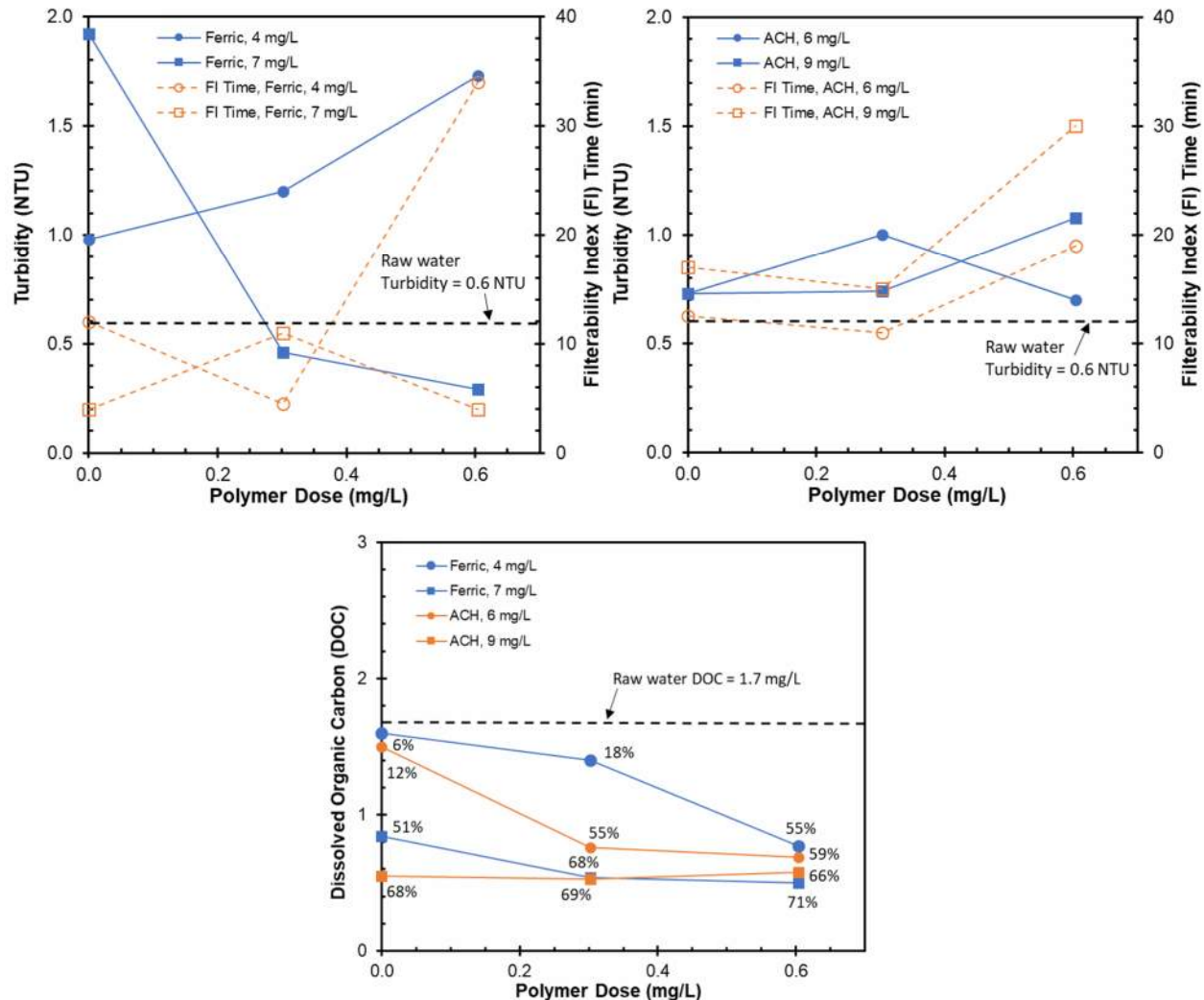


Figure 3. Performance of ferric and ACH assisted by polyamine Clarifloc C359 during flocculation

Although **Figure 3** shows that an increasing dose of polymer seems to give DOC removal a boost, the overall performance during this test was remarkably poorer when compared to the first coagulant results shown in **Figure 2**. The first tests show ferric alone at 3 and 6 mg/L reduced DOC by 23% and 73%, respectively, but this new test shows ferric at 4 and 7 mg/L only drop DOC by 6% and 51%, respectively, based on the untreated water DOC level). It should be noted that the reduced performance in these polymer tests may be due to a lower starting DOC condition because of a change in water quality from one sampling carboy to the next (possibly due to a change in raw water quality conditions during the sampling event). Although the percentage removal results appeared less pronounced, the final DOC concentrations were similar.

For ACH, a previous dose of 6 mg/L provided 32% DOC removal, but this new test only achieved 12% removal. The decrease in performance here may also be due to the changes in DOC from one carboy to the next. This change in water quality challenges the interpretation of polymer test results.

3. SUMMARY AND RECOMMENDATIONS

This third round of jar testing continued to show that low coagulant doses have significant potential for pilot testing selection. A summary of findings from this last jar test round includes the following:

- All coagulants showed relatively good turbidity and FI time performance at a dose of less than 6 mg/L (e.g., good performance was observed at 3 mg/L),
- Ferric testing was not consistent (good turbidity reduction in the first test, poor turbidity reduction in the next test, and poor color removal and UVT conditions at a low dose),
- Organics (based on measuring settled water for DOC, true color, and UV₂₅₄ transmittance after filtering at 0.45-µm) were well removed by all coagulants at a dose greater than 6 mg/L,
- All coagulants removed greater than 70% organics at a dose of 9 mg/L,
- Similar to previous jar testing, these tests showed less TOC removal than DOC removal (i.e., organics removal may not be occurring during settling, but possibly during 0.45-µm filtration),
- Although testing with polyamine cationic polymer were difficult to interpret due to changes in raw water quality, there were noticed reductions in turbidity and organics with increasing polymer dose, indicating that good plant performance may be achievable with a lower coagulant dose in combination with polymer addition.

Based on results from this testing, the following recommendations are provided for pilot testing:

- Determine if low-dose conditions for alum, PACl, and ACH (e.g., possibly less than 3 mg/L) can provide sustained filter operations,
- Due to inconsistencies in ferric testing, try to determine if ferric can be eliminated from further consideration early in the pilot testing,
- Jar testing results for flocculant aid polymer had some inconsistencies possibly due to fluctuations in raw water quality, however, it should be evaluated during the pilot to determine if it can aid in sustained filter runs and improve organics removal while also reducing coagulant dose.

Attachment A: Raw Data

Bull Run Water Jar Test Results: Round 3

Phase	Chemical	Coag Dose (mg/L)	Bicarb Dose (mg/L)	Polymer Dose (mg/L)	Raw or Settled Water												FI Test		Source water at time of sampling (4/9/2019): pH ? Temp: 3.8 C Turbidity: 2-3 NTU Conductivity: ?
					Floc Start Temp (degC)	SW Temp (degC)	pH	Alk (mg/L-CaCO3)	Turb (ntu)	Color, App	Color, True	UV254	UV254 (0.45um)	UVT (0.45um)	DOC (mg/L)	TOC (mg/L)	Turb (ntu)	Time (min)	
Raw Water	Day 1						6.5	5.6	0.84	23	13	0.087	0.086	82%	2.2	2.3			TOC/DOC and turbidity lower in this raw water sample compared to previous day. This should be noted when reviewing results. In test 4, ACH control test, the TOC/DOC were 2.5 mg/L, so TOC/DOC was variable (1.7-2.5 mg/L) in raw waters. RW not tested
	Day 2						6.8	5.2	0.56	22	14	0.088	0.086	82%	1.7	1.7			
	Day 3																		
Phase 1 (bicarb added to target min pH ~6.0 and min alk ~6 mg/L-CaCO3)	Alum	0	0.0		11.1	14.4	6.6	5.0	0.57	18	13	0.089	0.085	82%	2.5	2.4	0.54	6	Excellent DOC and color reduction at 9-15 mg/L doses. Turbidity reduction in FI tests not great, perhaps due to inadequate alkalinity? Bicarb dosing was off and so pH and alkalinity were lower than target minimums.
		3	0.0		11.1	14.3	6.6	3.8	0.77	21	14	0.089	0.084	82%	1.9	1.9	0.48	6	
		6	1.3		11.2	14.6	6.5	3.1	1.73	28	2	0.095	0.021	95%	0.8	1.9	1.29	5	
		9	2.5		11.1	14.5	6.3	3.0	1.85	30	2	0.078	0.011	97%	0.6	1.9	0.31	10	
		12	3.8		11.1	14.6	6.0	2.3	2.11	32	1	0.095	0.009	98%	0.5	1.8	0.85	13	
	Ferric Chloride	15	5.1		11.4	14.6	5.8	1.7	1.94	27	1	0.095	0.008	98%	0.6	1.9	1.15	9	Excellent turbidity reduction and TOC reduction in both SW and filtered water samples at 6 to 12 mg/L. Phase 2: Test 4 and 7 mg/L with polymer?
		0	0.0		11.0	16.0	6.9	5.2	0.51	20	12	0.083	0.083	83%	2.2	2.2	0.38	5	
		3	2.4		10.9	15.8	6.4	4.3	1.08	36	28	0.158	0.149	71%	1.7	1.8	0.59	3	
		6	6.8		11.0	15.8	6.1	3.3	0.80	14	1	0.053	0.012	97%	0.6	1.0	0.24	5	
		9	11.6		11.0	15.9	6.1	4.5	0.44	7	1	0.026	0.008	98%	0.5	0.7	0.11	7	
	PACI (PAX-18)	12	17.6		11.0	15.8	6.1	4.4	0.15	8	0	0.023	0.006	99%	0.4	0.7	0.12	11	Performance similar to ACH. Did not have opportunity to test again in Phase 2.
		15	24.0		11.2	16.2	6.1	6.5	0.14	8	1	0.025	0.005	99%	0.8	0.9	0.08	4	
		0	0.0		10.7	16.4	7.0	6.2	0.57	20	13	0.082	0.081	83%	2.9	2.8	0.34	5	
		3	0.0		10.7	15.4	6.6	4.7	0.53	20	13	0.085	0.081	83%	1.7	1.7	0.37	7	
		6	0.0		10.8	15.5	6.4	3.4	1.43	25	11	0.091	0.050	89%	1.2	1.7	1.14	5	
	ACH (PAX-XL19)	9	2.4		10.8	15.1	6.4	4.7	1.29	19	2	0.056	0.012	97%	0.6	1.5	0.20	4	Excellent DOC reduction at 9 and 12 mg/L doses. Phase 2: Test 6 and 9 mg/L with polymer?
		12	5.0		10.8	14.9	6.4	4.7	1.73	37	1	0.091	0.007	98%	0.5	1.7	0.37	13	
		15	7.6		10.9	15.0	6.4	5.8	1.53	24	1	0.092	0.008	98%	0.9	2.2	0.92	6	
		0	0		8.2	15.6	7.0	5.2	0.48	19	13	0.087	0.084	82%	2.5	2.5	0.37	3	
		3	0		8.0	15.2	6.8	5.1	0.48	20	14	0.086	0.083	83%	1.8	1.8	0.42	5	
Phase 2 (Primary Coagulants with cationic polymer polydadmac Clarifloc C359 dosed at 0, 0.3, and 0.6 mg/L)	Ferric Chloride	6	0		8.0	15.2	6.8	5.1	0.63	20	13	0.084	0.079	83%	1.7	1.7	0.48	3	At 4 mg/L ferric dosing, FI turbidity was very high even with addition of polymer. Addition of 0.6 mg/L poly with 4 mg/L ferric did reduce dissolved color and DOC. Poly benefit observed in 7 mg/L dosing in turbidity reduction. Results not quite consistent with Phase 1 dosing at 6 mg/L.
		9	0		8.0	16.0	6.8	4.7	0.87	20	1	0.061	0.009	98%	0.6	1.7	0.17	11	
		12	0		8.0	15.3	6.7	4.8	0.95	26	1	0.087	0.007	98%	0.5	1.7	0.53	9	
		15	0		8.2	16.0	6.6	4.6	0.68	21	4	0.086	0.023	95%	1.3	2.4	0.63	5	
		0	0		8.2	16.0	6.6	4.6	0.68	21	4	0.086	0.023	95%	1.3	2.4	0.63	5	
	ACH (PAX-XL19)	4	3.8	0.0	8.9	14.3	6.6	6.5	0.98	39	30	0.182	0.159	69%	1.6	1.7	0.77	12	Poly benefit observed in lower 6 mg/L ACH dosing. FI durations somewhat elevated in all samples. FI turbidities very low. Best test results appear to be at 9 mg/L ACH with 0 or 0.3 mg/L poly, in terms of turbidity reduction, FI turbidity, and DOC reduction.
		4	3.8	0.3	8.8	13.7	6.5	6.6	1.20	42	24	0.182	0.122	76%	1.4	1.6	1.00	5	
		4	3.8	0.6	8.8	14.0	6.5	5.9	1.73	47	3	0.184	0.025	94%	0.8	1.5	1.11	34	
		7	8.6	0.0	8.9	14.1	6.5	7.6	1.92	57	5	0.243	0.032	93%	0.8	1.8	1.62	4	
		7	8.6	0.3	9.2	14.1	6.6	9.3	0.46	17	1	0.057	0.013	97%	0.5	0.9	0.20	11	
		7	8.6	0.6	9.3	14.4	6.6	8.8	0.29	11	1	0.036	0.010	98%	0.5	0.7	0.12	4	
		6	0	0.0	11.3	15.9	6.8	5.4	0.73	21	7	0.089	0.047	90%	1.5	1.9	0.55	13	
		6	0	0.3	11.1	15.0	6.8	5.2	1.00	23	2	0.087	0.020	95%	0.8	1.6	0.47	11	
		6	0	0.6	11.0	14.8	6.9	5.0	0.70	14	2	0.052	0.015	97%	0.7	1.5	0.13	19	
		9	0	0.0	11.0	14.8	6.8	0.0	0.73	16	1	0.054	0.010	98%	0.6	1.7	0.08	17	
		9	0	0.3	11.1	15.0	6.8	4.6	0.74	16	1	0.055	0.008	98%	0.5	1.5	0.09	15	
		9	0	0.6	11.2	15.5	6.8	5.0	1.08	25	1	0.085	0.007	98%	0.6	1.5	0.10	30	

Legend	FI Test				Settled Water							
	Turb (ntu)	FI	Time (min)	Alk	Turb (ntu)	Color, App	Color, True	UV254	UV254 (0.45um)	UVT (0.45um)	DOC (mg/L)	TOC (mg/L)
	≤0.25	≤3	≤15	>6	≤0.3	≤5	≤5	≤0.02	≤0.02	≤0.93	≤0.8	≤0.8
	0.25<x≤0.4	3<x≤5	15<x≤20	4<x≤6	0.3<x≤0.4	5<x≤15	5<x≤15	0.02<x≤0.04	0.02<x≤0.04	0.93<x≤0.97	0.8<x≤1	0.8<x≤1
	>0.4	>5	>20	<4	>0.4	>15	>15	>0.04	>0.04	>0.97	>1	>1
Period 3 Jar Test Findings: - Color values shown for ALL TESTS based on DR1900 method at fixed wavelength.												

Appendix B: Bench-Scale Ozone Demand-Decay Testing Report

Brown and Caldwell, May 2019

Bench-Scale Ozone Demand-Decay Testing

Portland Bull Run Surface Water

May 24, 2019

Bench-scale ozonation demand-decay testing was conducted on Portland Bull Run surface water at the University of Colorado Boulder SEEL Laboratory.

Source Water Characteristics

Two 10-liter cubitainers of Portland Bull Run surface water was collected by the Portland Water Bureau (PWB) on March 1st, 2019. Water samples were collected at the 2PIS intake and measured for bulk water quality parameters summarized in Table 1. Water samples were stored on ice until shipped overnight to University of Colorado Boulder on March 11th, 2019. Water samples were stored at the CU laboratory at 4°C until the ozone demand-decay testing was conducted on April 2nd, 2019.

Table 1. Initial Sampling Raw Water Quality

TOC (mg/L)	DOC (mg/L)	Turbidity (NTU)	pH	Conductivity (μ S/cm)	Alkalinity (mg/L as CaCO ₃)	UV ₂₅₄ (abs)
1.4	1.4	0.235	7.05	19.6	7.8	0.047

Water quality provided by the Portland Water Bureau.

Bench-Scale Testing Approach

Bench-scale ozone testing was conducted to understand ozone decay rates and ozone demand for Portland Bull Run surface water. Sample water was ozonated using the batch aqueous stock solution method described in *Standard Methods for the Examination of Water and Wastewater 22nd edition* 2350 D. Aqueous ozone concentrations were measured using the direct UV method at 260 nm wavelength and dosed at four target applied ozone doses of 0.5, 1.0, 1.5, and 2.0 mg/L. Ozone residuals were analyzed using Hach ozone reagent AccuVac ampules at seven detention times of 0.5, 1, 2, 5, 10, 15, and 30 minutes. Bench testing was conducted at a target temperature of 4°C to simulate winter (cold) raw water conditions. Water quality parameters of DOC, TOC, UV₂₀₀₋₈₀₀, and apparent color were measured throughout the testing to evaluate the transformation of organic compounds and potential impacts on disinfectant by-product precursors. Raw sample water quality analysis collected pre-ozonation is summarized in Table 2.

Table 2. Raw Water Quality (Pre-Ozonation)

TOC (mg/L)	DOC (mg/L)	pH	Temperature (°C)	Apparent Color (UV ₄₆₅)
1.21	1.13	7.0	4	0.014

Water quality analyzed at CU Boulder Laboratory

Procedures

Batch aqueous stock solution ozonation testing was conducted in 1 L amber bottles. All glassware was prepared ozone demand-free (ODF) by acid wash, soaking in ozone residual Milli-Q water, and dried in a high-temperature oven. Ozone stock solution was generated in a jacketed ozone reactor with highly purified Milli-Q water (Figure 1). The Milli-Q water was chilled to 2°C and saturated with ozone to achieve a concentration ranging from 23-30 mg/L O₃. Aqueous ozone concentrations were calculated based on Beer's Law and UV absorbance at 260 nm wavelength (Equation 1).

Equation 1.
$$C_{Ozone} = \frac{Abs_{260}}{\epsilon \times L} (MW_{Ozone} \times 1000)$$

Ozone molar absorptivity, $\epsilon = 3300 \text{ M}^{-1} \text{ cm}^{-1}$

Cell pathlength, $L = 1 \text{ cm}$

Ozone molecular weight, $MW_{Ozone} = 48 \text{ g/mol}$

All ozone testing was conducted in a temperature-controlled room set at 4°C. 900 mL of sample was measured and poured into ODP amber bottles. Sample water temperature measured with a thermometer throughout the testing. Aliquots of ozone stock solution were added to sample bottles to achieve target ozone applied dose. Sample bottles were immediately capped and inverted 4 times to saturate the sample volume. Aliquots of ozonated water samples were poured into 50 mL ODF beakers at each designated detention times and measured for ozone residual and apparent color. Ozone residuals were measured using the indigo colorimetric method via Hach AccuVac ampoules (Figure 2). Apparent color samples were measured at UV₄₆₅ and unfiltered. At a detention time of 10 mins, aliquots of ozonated samples were quenched with sodium sulfite and measured for TOC and DOC. At the completion of the ozone decay testing (no ozone residual), sample waters were UV scanned from 200 to 800 nm wavelengths.



Figure 1. Jacketed Ozone Reactor

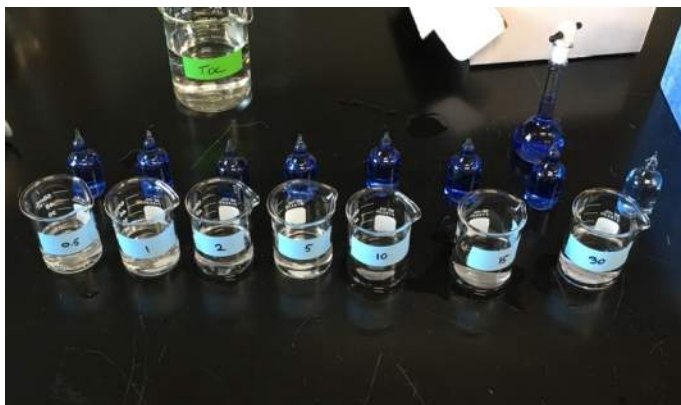


Figure 2. Hach Ozone Reagent AccuVac Ampoules

Results and Discussion

Applied ozone doses were calculated from the ozone stock solution concentration and volume applied to each sample. The difference between the applied ozone dose and ozone residual, measured at 30 seconds, was identified as the instantaneous ozone demand. On average, the instantaneous ozone demand was 0.43 mg/L O₃. Assuming a pseudo first-order kinetic reaction, reaction rate constants were calculated for the sample ozone doses. The reaction rate coefficient for the low ozone dose sample was not calculated, due to fact that there was no measurable ozone residual after 30 seconds. Figure 3 shows the reaction rate decreases with increasing applied ozone dose.

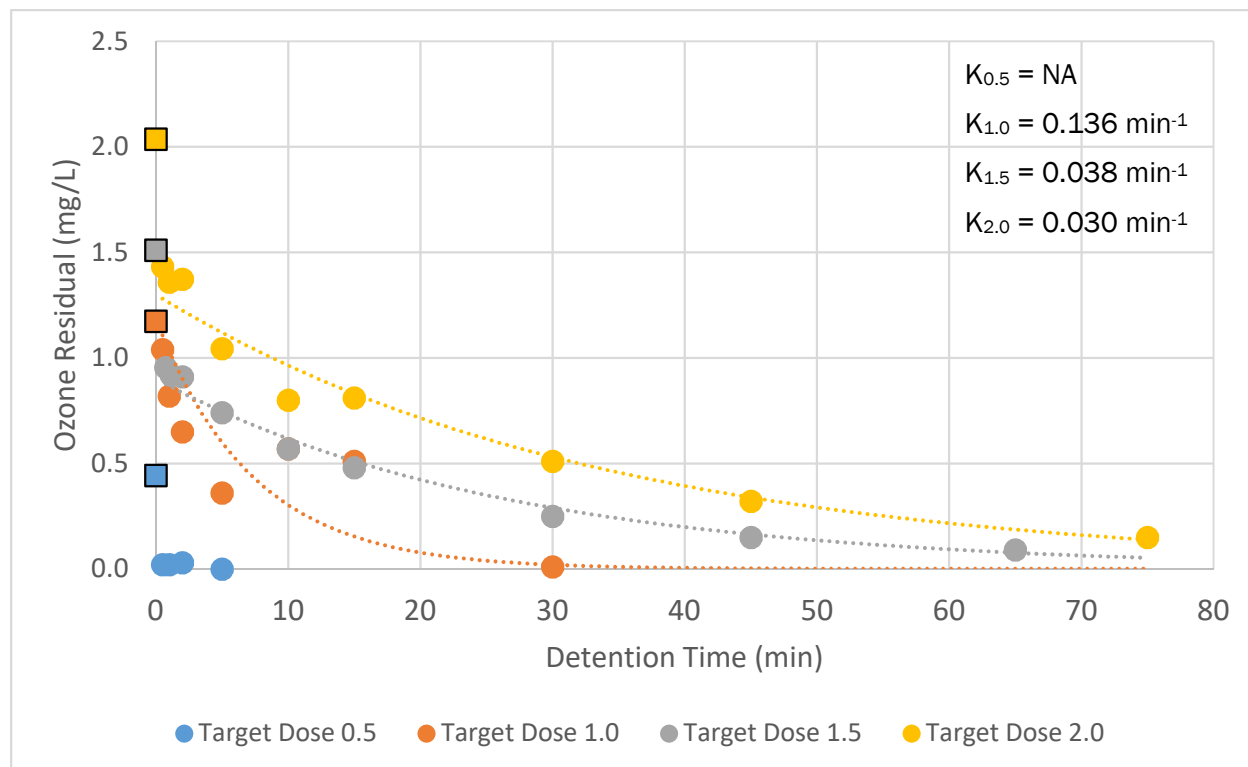


Figure 3. Ozone Residual Over Time

Water quality analysis of the ozonated samples is summarized in Table 3. For all applied ozone doses, TOC and DOC concentrations were not significantly impacted. Ozonation at typical drinking water doses does not mineralize natural organic matter (NOM). Ozone preferentially oxidizes electron rich moieties (i.e. olefinic structures and aromatic alcohols) transforming organic matter into smaller compounds. The ozone transformation of organic matter is illustrated in Figure 4 with significant reduction of UV₂₅₄ and apparent color. Ozone dose did not have a significant impact on pH.

Table 3. Water Quality of Ozonated Samples							
Ozone Target Dose (mg/L)	Time (min)	UV ₄₆₅ (Color)	Residual Ozone (mg/L as O ₃)	pH	TOC (mg/L)	DOC (mg/L)	Temperature (C)
Influent	--	0.014	--	7.0	1.21	1.13	4
0.5	0.5	0.012	0.02		1.17	1.08	4
	1		0.02				4
	2	0.011	0.03				4
	5	0.017	0				4
	10	0.014	--				4
	15		--				4
	30		--				4
	30 +		--	7.1			4
1	0.5	0.012	1.04		1.17	1.15	4
	1	0.014	0.82				4
	2		0.65				4
	5	0.006	0.36				4
	10	0.006	0.57				4
	15		0.51				4
	30		0.01				4
	30 +		--	7.1			4
1.5	0.5	0.009	0.96		1.15	1.07	4
	1		0.92				4
	2	0.003	0.91				4
	5	0.003	0.74				4
	10	0.002	0.57				4
	15		0.48				4
	30		0.25				4
	45		0.15				4
	65		0.09				4
	65+		--	7.0			4
2.0	0.5	0.12	1.43		1.2	1.1	4
	1		1.36				4
	2	0.1	1.37				4
	5	0.004	1.04				4
	10	0.004	0.80				4
	15		0.81				4
	30		0.51				4
	45		0.32				4
	75		0.15				4
	75 +		--	7.0			4

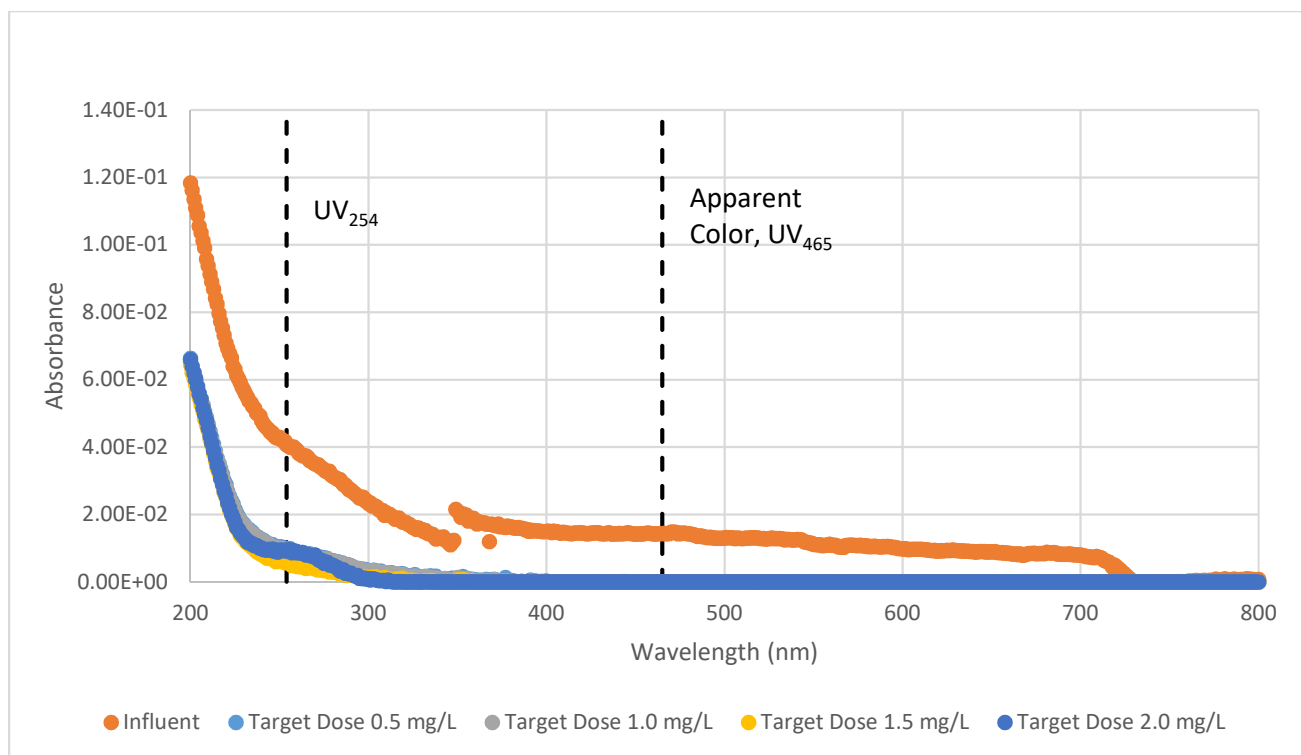


Figure 4. UV scan of Ozonated Samples

The conclusions of the bench-scale ozone demand-decay testing are summarized below:

- The raw water exhibited an average instantaneous ozone demand of 0.43 mg/L.
- As applied ozone dose increases, the ozone decay constant decreases ($K_{1.0} = 0.136 \text{ min}^{-1}$, $K_{1.5} = 0.038 \text{ min}^{-1}$, $K_{2.0} = 0.030 \text{ min}^{-1}$).
- Ozone did not impact TOC and DOC concentrations .
- Ozone significantly reduced UV_{254} and apparent color (@ UV_{465}).
- pH was not significantly impacted by ozone dose.
- Ozone residual was measurable at greater than 65 minutes for higher ozone doses (1.5 and 2.0 mg/L) where there was not sufficient ozone demand,

Appendix C: Simulated Distribution System and Disinfection Evaluation

Portland Water Bureau, October 2019

Memo

To: Treatment Pilot Operations Team
TAC: Issam Najm, Ph.D., Mark LeChevallier, Ph.D.

From: Anna Vosa, PE, PWB

Date: February 5, 2020

Re: October 2019 Simulated Distribution System and Disinfection Evaluation

Summary

The Bull Run Treatment Pilot Study Work Plan includes a series of Simulated Distribution System (SDS) tests throughout the 12-month pilot testing period to evaluate the effect of filtration and various treatment approaches on the formation of disinfection byproducts (DBPs) and chlorine demand and decay (CDD) during disinfection with free chlorine and chloramines. This memorandum summarizes the results of the October 2019 SDS evaluation. This testing evaluation was proposed as a trial run ahead of four quarterly SDS evaluations that will be completed around the same time the Portland Water Bureau (PWB) collects Stage 2 Disinfectants and Disinfection Byproducts Rule (D/DBPR) compliance samples. Historically, organic matter in the Bull Run water supply and DBPs formed during disinfection and distribution have been at the highest levels in the fall compared to any other time of the year.

A goal of the Bull Run Treatment Project is to reduce DBPs to below 50% of the regulatory limits. The Stage 2 D/DBPR regulates two groups of DBPs: total trihalomethanes (THMs or TTHM) and haloacetic acids (HAAs or HAA5). The Maximum Contaminant Level (MCL) for TTHM is 80 µg/L and for HAA5 is 60 µg/L. Compliance is based on a locational running annual average (LRAA) of samples collected throughout the distribution system.

The pilot plant is divided between two treatment trains, referred to as Train 1 and Train 2. Each treatment train consists of a pre-oxidant contactor, rapid mix, flocculation, sedimentation, and three filter columns. Train 1 serves Filters 4, 5, and 6 and Train 2 serves Filters 1, 2, and 3. Media depth and characteristics for each filter are identified in Table 3. By operating two independent pilot treatment trains, PWB has the unique opportunity to directly compare pre-treatment approaches and filter configurations side-by-side to directly evaluate the benefits of various design elements and operational approaches.

When the pilot plant was sampled for the October SDS evaluation, each train was operated in conventional treatment mode with coagulant polyaluminum chloride (PACl) dosed at 3.5 mg/L and nonionic filter aid polymer dosed at 0.010 mg/L. Train 1 was pre-chlorinated with a dose of 0.3 mg/L-Cl₂ and 13 minutes of contact time and Train 2 was pre-ozonated with a dose of 1.0 mg/L-O₃ and 13 minutes of contact time. The raw water turbidity was 0.5 NTU turbidity, TOC was 1.4 mg/L TOC, and the temperature was 12°C.

The objectives of the October SDS evaluation were to evaluate the following on the resulting disinfectant demand and decay and DBP formation after disinfectant dosing:

- Pre-oxidation using ozone dosed at 1 mg/L (Train 2) versus chlorine dosed at 0.3 mg/L (Train 1)
- Filtration using GAC media versus anthracite media
- Raw, unfiltered water versus water treated using the combination of pre-oxidation, coagulation, flocculation, sedimentation, and filtration

Portland Water Bureau

Water Quality



Tests were carried out on samples collected from 8 locations, including the pilot raw inlet, all six filter effluents, and PWB's Lusted Outlet distribution system entry point. Pilot raw inlet and filter effluent samples were treated with disinfection and corrosion control chemicals using doses that mimic conservative future treatment targets and compared with PWB's Lusted outlet entry point water over a 14-day period. Treatment doses and conditions used during the October SDS tests are shown in Table 1. Treatment of pilot raw and filtered samples included sodium hypochlorite dosing to target a free chlorine residual of 2.5 mg/L after 60 minutes of contact time, followed by the addition of ammonium chloride, sodium bicarbonate, and sodium carbonate to convert free chlorine to monochloramine and adjust pH and alkalinity to 9.0 and 30 mg/L-CaCO₃, respectively. The Lusted Outlet sample is fully treated PWB water collected at the distribution system entry point. At the time of testing, the Lusted Outlet sample had been treated at Headworks with 3.7 mg/L-Cl₂ (gaseous chlorine), and after 320 minutes of free chlorine contact time in the conduits, the water had the target free chlorine residual of 2.5 mg/L before dosing at Lusted Hill Treatment Facility with aqueous ammonia to form chloramines and sodium hydroxide to target PWB's finished water pH of 8.2.

Table 1. Post-Filtration Treatment Targets used in October SDS Testing

Post-Treatment Element	Lusted Outlet (PWB Entry Point)	Pilot Samples (unfiltered raw water and filter effluent)	Notes
Free Chlorine Contact Time	Contact time in Conduit 3 was 320 minutes on day of October SDS Testing	60 minutes	PWB is currently required to provide 3.0-log <i>Giardia</i> inactivation via free chlorine contact (30 to 90 minutes contact time depending on temperature and chlorine dose). A conventional plant would be required to provide 0.5-log inactivation following filtration (6 to 30 minutes contact time depending on temperature and chlorine dose). 60 minutes was selected as a conservative target.
Free Chlorine Residual Target (at end of Contact Time)	2.5 mg/L	2.5 mg/L	PWB Jan-June target is 2.2 mg/L and July-Dec target is 2.5 mg/L. 2.5 mg/L is used as a conservative target as, if anything, it may be desired to reduce the chlorine target once filtration is operational.
Secondary Disinfectant	Chloramines (ammonia dosed at Cl ₂ :NH ₃ -N ratio of 4.9:1)	Chloramines (ammonia dosed at Cl ₂ :NH ₃ -N ratio of 4.5:1)	Ammonia is added with corrosion treatment chemicals to convert free chlorine to monochloramine. For the purposes of pilot testing, it is assumed that chloramines will continue to be used for secondary disinfection.
Corrosion Control pH Alkalinity	Sodium Hydroxide pH = 8.2 No purposeful alkalinity adjustment	Sodium Bicarbonate, Sodium Carbonate pH = 9.0 Alk. = 30 mg/L-CaCO ₃	Current corrosion control pH target is 8.2. Proposed ICCT will increase pH and alkalinity to the ranges of 8.6-9.0 and 25-40 mg/L-CaCO ₃ at entry point to maintain a pH of 8.6 in the system.

Following treatment, all samples were stored in 1-L amber glass bottles with temperature maintained between 8°C and 15°C, a range similar to the October temperature in PWB's distribution system. Sampling

Portland Water Bureau

Water Quality



for water quality analyses, including THMs and HAAs, was performed at the beginning, middle, and end of the 14-day SDS period. Results for 14-day DBP concentrations and CDD are summarized in Figures 1 and 2.

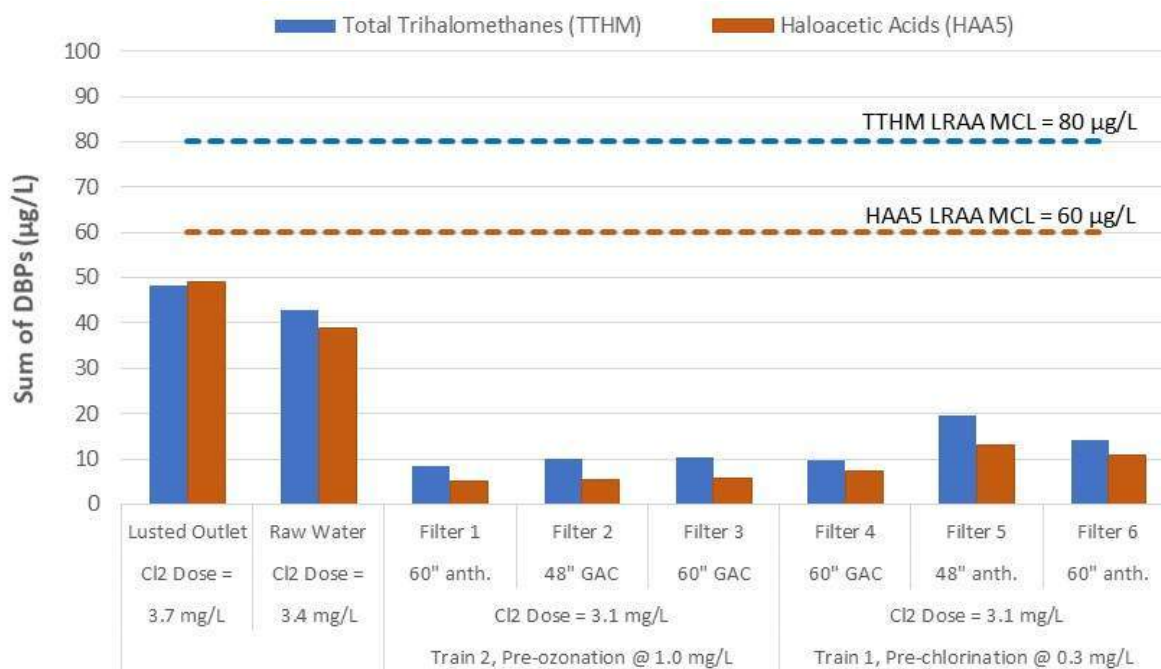


Figure 1. SDS Test Results for 14-day Total Trihalomethanes and Haloacetic Acids



Figure 2. SDS Test Results for Chlorine Demand & Decay

The following is a summary of key findings from the October SDS Evaluation:

Comparison of Results for SDS Tests Conducted on Unfiltered Samples

- In the Lusted Outlet sample, chlorine dropped 1.1 mg/L during the free chlorine contact period and 1.0 mg/L during the subsequent 14-day SDS period, representing a combined CDD of 2.1 mg/L. Over the same timeframe, the chlorine in the Pilot Raw Water sample dropped 1.4 mg/L, a difference of 44% from the Lusted Outlet sample. The reduction in the chlorine demand is thought to be associated with the shorter free chlorine contact time (60 minutes vs. 320 minutes) as well as the higher pH target (9.0 vs. 8.2). While PWB does not have much flexibility in controlling the time water travels in the conduits and contacts with free chlorine, this result is meaningful as it indicates that chlorine could be more stable in the distribution system following implementation of Improved Corrosion Control Treatment (ICCT) in 2022.
- The 14-day HAA5 and TTHM results for the treated raw water sample were 22% lower and 11% lower, respectively, than levels in the Lusted outlet sample. These reductions are associated with the lower chlorine dose, lower free chlorine contact time, and higher pH used for the pilot raw water sample.
- DBP concentrations in unfiltered samples increased significantly over the 14-day SDS period. HAA5 concentrations increased 22% in the Lusted Outlet sample and 30% in the Pilot Raw Water sample. TTHM concentrations increased 43% in the Lusted Outlet sample and 64% in the Pilot Raw Water sample. This finding is consistent with what is observed in historical PWB DBP sampling and indicates, even though chloramines are used for secondary disinfection, that DBPs increase significantly during distribution.

Comparison of Filtered Samples with Lusted Outlet Sample

- CDD over the combined free chlorine contact and 14-day chloraminated SDS period ranged between 0.75 mg/L and 1.4 mg/L in filtered SDS samples. Compared with the Lusted Outlet sample, this represents a decrease in CDD of 35-66%.
- DBPs in all filtered samples were reduced well below 50% of their respective MCLs. As shown in Figure 1, the 14-day DBP results for all filtered samples were all below 20 ppb.
- Chlorine loss during the 14-day chloraminated SDS period was significantly affected by the chlorine-to-ammonia dosing ratio. For example, despite common pre-treatment and similar media (anthracite over sand), chlorine dropped 0.99 mg/L in the Filter 5 sample and 0.31 in the Filter 6 sample during the 14-day chloraminated SDS period. The chlorine-to-ammonia dosing ratio was calculated to be 5.3 for Filter 5 and 4.4 for Filter 6.

Comparison of Filtered Samples Treated with and without Ozone

- CDD, inclusive of pre-chlorine, measured in samples from ozonated Filters 1 and 3 was higher than in their pre-chlorinated counterparts (Filters 4 and 6). This result suggests that the ozonated train is producing higher levels of oxidizable material than the pre-chlorinated train. Additional investigation is needed to confirm this result and identify improvements that can be made.
- DBP concentrations were lower in samples collected from the pre-ozonated filters than in samples collected from the pre-chlorinated filters. HAAs measured after 14 days ranged between 5.0 and 5.8 µg/L in ozonated samples and 7.4 and 13.0 µg/L in pre-chlorinated samples. THMs measured after 14 days ranged between 8.5 and 10.4 µg/L in pre-ozonated samples and 9.7 to 19.5 µg/L in pre-chlorinated samples.

Comparison of Samples Filtered with GAC vs. Anthracite

- Within Train 1 (pre-chlorine), the GAC-filtered sample (Filter 4) had the lowest DBP levels. Within Train 2 (pre-ozone), samples collected from the GAC filters (Filters 2 and 3) did not have lower levels of DBPs than the anthracite filter (Filter 1). While the GAC filters do consistently remove more TOC than the anthracite filters, their benefit for the reduction of DBPs and chlorine demand appears to be modest.

The results of the October 2019 SDS Evaluation indicate that conventional treatment is highly effective for controlling the formation of regulated DBPs and reducing the loss of chlorine during disinfection and distribution of PWB's water. Future SDS tests will incorporate analysis of unregulated DBPs and Flavor Profile Analysis testing.

Approach and Methods

The SDS testing approach and methods are described in detail in the *Simulated Distribution System Bench Testing Plan and Standard Operating Procedure* (Appendix A).

Samples used for the October SDS test were collected from the raw pilot inlet, each pilot filtered effluent, and PWB's entry point at Lusted Hill Treatment Facility (LHTF) outlet ("Lusted Outlet"). Table 2 identifies treatment targets used during the October SDS test. Pilot raw water and pilot filtered samples were dosed with disinfection and corrosion control treatment chemicals, as applicable, according to the desired treatment targets. The Lusted Outlet samples were collected from LHTF outlet off Conduit 3 and were not treated further as the water was fully treated finished water.

Each test within the evaluation involves filling 1-L amber glass bottles from a given sample location, performing treatment dosing, storing, and then removing for water quality analyses at the appropriate time, according to their designation in the treatment scheme:

- **Initial Water "IW"** – Untreated sample is analyzed for: temperature, pH, alkalinity, TOC, DOC, apparent color, and UV254.
- **Disinfected Water "DW"** – Sample is dosed with sodium hypochlorite to target 2.5 ± 0.2 mg/L chlorine residual following desired free chlorine contact time (generally 60 minutes); sampled at end of free chlorine contact period for: temperature, pH, alkalinity, apparent color, free chlorine, and total chlorine.
- **Finished Water/Entry Point "T0"** – Sample is dosed the same as the DW sample; at end of free chlorine contact period is dosed with secondary treatment chemicals (ammonium chloride, sodium carbonate, and sodium bicarbonate) to convert free chlorine to monochloramine and adjust pH and alkalinity to desired finished water targets (pH 9.0 ± 0.2 and alkalinity 30 ± 3 mg/L-CaCO₃); sampled 10 minutes following secondary dosing for: temperature, pH, alkalinity, apparent color, total chlorine, monochloramine, free/total ammonia, total trihalomethanes (TTHM), and haloacetic acids (HAA5).
- **7-day (T7)** – Same dosing as T0 sample; stored in dark, temperature-controlled location (targeting current Powell Butte Reservoir outlet temperature $\pm 2.5^\circ\text{C}$); sampled 7 days following dosing for same water quality parameters analyzed in T0 sample.
- **14-day (T14)** – Same dosing as T0 sample; stored in dark, temperature-controlled location (targeting current Powell Butte Reservoir outlet temperature $\pm 2.5^\circ\text{C}$); sampled 14 days following dosing for same water quality parameters analyzed in T0 sample.

Initial Water Quality and Treatment Conditions

Table 3 summarizes the initial sample information, including pilot operational conditions at the time of sampling and initial water quality, for each of the samples evaluated in the October SDS evaluation. For this sampling event, both treatment trains were operated in conventional treatment mode and provided with PACl (PAX-18 dosed at 3.5 mg/L) and nonionic filter aid polymer (Clarifloc N-6310 dosed at 0.010 mg/L). Train 1 (serves Filter nos. 4, 5, and 6) was pre-chlorinated with sodium hypochlorite at a dose of 0.3 mg/L-Cl₂ and Train 2 (serves Filter nos. 1, 2, and 3) was pre-ozonated with a dose of 1.0 mg/L-O₃ and 13 minutes of contact time.

Pilot raw water contained 0.5 NTU turbidity. Raw water contained 1.4 mg/L TOC (SUVA = 4.2 L/mg-m) and filtered samples contained between 0.4 to 0.6 mg/L in the filtered samples (>50% reduction). TOC was slightly higher in pre-ozonated filter effluents than pre-chlorinated filter effluents. Within a similar process train, TOC levels were slightly lower in samples from GAC filters than from anthracite filters.

While the testing plan assumed that all sampling and testing would be initiated on November 22, the effort spilled into November 23 as the operations team encountered some unanticipated challenges with analytical equipment and the pilot process. While certain samples had higher than optimal turbidity and particle count values due to either sampling at suboptimal times in the filter run or due to suboptimal treatment performance, in all filtered samples, TOC was reduced 50% or so from raw levels and apparent color readings were zero.

Disinfection and corrosion control treatment doses and resulting chlorine residual, pH, and alkalinity measurements are provided in Table 4.



Table 2. October 2019 SDS Test Treatment Scenario and Sampling Matrix

Treatment Scenario	Upstream Treatment/Sample Source	Sample Location	Primary Disinfection		Secondary Disinfection		Corrosion Control		Target Temp during SDS Test (deg. C)	WQ Parameters Sampled				
			Free Chlorine Residual Target (mg/L)	Contact Time (min)	Secondary Disinfectant	Target Ratio	pH Target	Alkalinity Target (mg/L- CaCO3)		Initial Water (IW)	Disinfected Water (DW)	T0 ("EP")	T7	T14
1	Raw Water	Raw Pilot Inlet	2.5	60	Chloramine	4.5:1	9.0	30	Monthly Powell Butte Res Outlet Avg (11 ± 2.5 deg)	pH, temp, alkalinity, UV254, apparent color, TOC/DOC	pH, temp, alkalinity, UV254, TOC, apparent color, free chlorine, total chlorine	pH, temp, alkalinity, UV254, apparent color, total chlorine, monochloramine, free/total NH3, TTHM, HAA5	pH, temp, alkalinity, UV254, apparent color, total chlorine, monochloramine, free/total NH3, TTHM, HAA5	pH, temp, alkalinity, UV254, apparent color, total chlorine, monochloramine, free/total NH3, TTHM, HAA5
2	Pilot Train 2: 1.0 mg/L ozone, 3.5 mg/L PACl, 0.010 mg/L FAP	Filtered Effluent 1	2.5	60	Chloramine	4.5:1	9.0	30						
3		Filtered Effluent 2	2.5	60	Chloramine	4.5:1	9.0	30						
4		Filtered Effluent 3	2.5	60	Chloramine	4.5:1	9.0	30						
5	Pilot Train 1: 0.3 mg/L pre-chlorination dose, 3.5 mg/L PACl, 0.010 mg/L FAP	Filtered Effluent 4	2.5	60	Chloramine	4.5:1	9.0	30						
6		Filtered Effluent 5	2.5	60	Chloramine	4.5:1	9.0	30						
7		Filtered Effluent 6	2.5	60	Chloramine	4.5:1	9.0	30						
8	Lusted Outlet, System Entry Point	Conduit 3 Lusted Outlet	2.5	320	Chloramine	4.9:1	8.2	n/a			n/a	n/a		
9	Pilot Train 2: 1.0 mg/L ozone, 3.5 mg/L PACl, 0.02 mg/L FAP	Filtered Effluent 1	2.5	30	n/a	n/a	n/a	n/a	n/a	n/a	pH, temp, alkalinity, UV254, TOC, apparent color, free chlorine, total chlorine, TTHM, HAA5	Samples not carried into SDS period; no sampling		
10		Filtered Effluent 1	2.5	90	n/a	n/a	n/a	n/a	n/a	n/a				
11	Pilot Train 1: 0.3 mg/L pre-chlorination dose, 3.5 mg/L PACl, 0.02 mg/L FAP	Filtered Effluent 6	2.5	30	n/a	n/a	n/a	n/a	n/a	n/a				
12		Filtered Effluent 6	2.5	90	n/a	n/a	n/a	n/a	n/a	n/a				

Table 3. Initial Water Quality and Operational Conditions

Sampled Location		Description	Unit Filtration Rate (gpm/sf)	Initial Water Quality and Operational Conditions										
				Sample Collection Time	Filter Run Time (@ sampling/total) (hr)	Turbidity (on-line) (NTU)	Turbidity (benchtop) (NTU)	Total Particle Count (count/mL)	Temp (deg. C)	pH	Alkalinity (mg/L- CaCO3)	TOC (mg/L)	UV254 (cm ⁻¹)	Apparent Color (CU)
Lusted Treatment Facility Outlet		Bull Run Entry Point	n/a	10/22/2019 8:51	n/a	0.57	-	n/a	12.2**	8.29	13.8	1.3	0.055	10
Raw Water		Pilot Raw Inlet	n/a	10/22/2019 10:20	n/a	0.76	0.48	4021	12.3	7.48	11.1	1.4	0.059	17
Train 2* - Conventional w/Pre-ozonation @ 1.0 mg/L	Filter 1 Effluent	60" anthracite/12" sand	12	10/23/2019 10:47	4.8/5.2	0.12	0.27	434	12.8	6.59	8.8	0.74	0.008	0
	Filter 2 Effluent	48" GAC/12" sand	8	10/22/2019 11:05	3.0/21.3	0.11	0.19	11	13.1	6.9	10.0	0.59	0.006	0
	Filter 3 Effluent	60" GAC/12" sand	12	10/22/2019 11:55	2.9/4.3	0.10	0.18	141	13.0	6.97	9.6	0.62	0.007	0
Train 1* - Conventional w/Pre-chlorination @ 0.3 mg/L-Cl2	Filter 4 Effluent	60" GAC/12" sand	12	10/22/2019 14:05	0.4/9.6	0.04	0.14	138	13.0	6.92	9.0	0.44	0.007	0
	Filter 5 Effluent	48" anthracite/12" sand	8	10/22/2019 13:30	5.0/24.5	0.01	0.07	1	12.8	6.90	8.9	0.57	0.010	0
	Filter 6 Effluent	60" anthracite/12" sand	12	10/23/2019 12:40	0.9/4.5	0.08	0.33	2	12.7	6.64	8.6	0.55	0.007	0

*Both treatment trains were operated in conventional (sedimentation) mode and coagulated with 3.5 mg/L PACl and dosed with 0.010 mg/L nonionic filter aid polymer.

**Measured at Headworks. Temperature monitoring not available at Lusted and temperature was not measured until after sample was transported to pilot plant.

Table 4. Actual SDS Test Dosing and Resulting Treated Water Quality

Sampled Location		SDS Dosing and Targets												
		Primary Disinfection Dosing			Secondary Treatments for Chloramination and Corrosion Control									
		Chlorine Dose (mg/L)	Free Chlorine Contact Time (min)	Free Chlorine Residual after Contact Period (mg/L)	Ammonia Dose (mg/L-N)	Applied Cl2:N Dosing Ratio	Final Total Chlorine (mg/L)	Final Mono-chloramine (mg/L)	Final Total Ammonia (mg/L-N)	Final Free Ammonia (mg/L-N)	Na2CO3 Dose (mg/L)	NaHCO3 Dose (mg/L)	Final pH	Final Alkalinity (mg/L- CaCO3)
Lusted Treatment Facility Outlet		3.7	320	2.52	0.51	4.9	2.62	2.43	0.46	0.09	-	-	7.84	13.8
Raw Water (Pilot Inlet)		3.4	60	2.72	0.56	4.9	2.60	2.47	0.5	<0.05	10	25	8.40	FE
Train 2 - Conventional w/Pre-ozonation @ 1.0 mg/L	Filter 1 Effluent	3.1	60	2.59	0.56	4.6	2.66	2.51	0.6	<0.05	12	27.5	8.77	34.8
	Filter 2 Effluent	3.1	60	2.74	0.56	4.9	2.59	2.50	0.5	<0.05	12	27.5	8.55	34.8
	Filter 3 Effluent	3.1	60	2.79	0.56	5.0	2.68	2.53	0.5	<0.05	12	27.5	8.54	34.5
Train 1 - Conventional w/Pre-chlorination @ 0.3 mg/L-Cl2	Filter 4 Effluent	3.1	60	3.02	0.67	4.5	3.03	2.85	0.6	0.03	12	27.5	8.64	34.3
	Filter 5 Effluent	3.1	60	2.95	0.56	5.3	2.78	2.45	0.5	<0.05	12	27.5	8.77	34.6
	Filter 6 Effluent	3.1	60	2.96	0.67	4.4	2.91	2.75	0.6	<0.05	12	27.5	8.60	34.4

*Target Cl₂:N ratio was 4.5 for pilot plant samples, with goal of dosing at ratio <5:1. The ratio was >5:1 in the Filter 5 sample.
**Final pH was not consistently measured within 15 minutes of sampling and therefore resulted in lower than expected pH results.

Table 5. Chlorine Residual Measurements and Demand and Decay Calculations

Sampled Location		Free Chlorine Contact Period					14-day SDS Period (Post-Secondary Treatment)			Chlorine Demand and Decay (CDD) Calculations								
		Pre-Chlor. Dose	Chlorine Dose	Chlorine Dose, inc. pre-chlor.	Free Chlorine Residual after Contact Period	Total Chlorine after Contact Period	0-day (10 mins after sec. trtmt)	7-day	14-day	CDD during free chlorine contact period	Total Chlorine Loss during Ammonia Addition	CDD 0-7 Days	CDD 7-14 Days	CDD 0-14 Days	CDD during free chlorine contact and SDS period	Percent Reduction from Lusted Sample during Free Chlorine Contact	Percent Reduction from Lusted Sample during 14- day SDS Period	Percent Reduction from Lusted Sample during free chlorine contact and 14-day SDS period
Lusted Treatment Facility Outlet		-	3.7	3.7	2.52	-	2.62	1.91	1.59	1.08		0.71	0.32	1.03	2.11			
Raw Water (Pilot Inlet)		-	3.4	3.4	2.72	2.77	2.60	2.26	2.04	0.68	0.17	0.34	0.22	0.56	1.24	42%	46%	44%
Train 2 - Conventional w/Pre- ozonation @ 1.0 mg/L	Filter 1 Effluent	-	3.1	3.1	2.59	2.64	2.66	2.37	2.20	0.51	-0.02	0.29	0.17	0.46	0.97	57%	55%	56%
	Filter 2 Effluent	-	3.1	3.1	2.74	2.85	2.59	2.06	1.89	0.36	0.26	0.53	0.17	0.70	1.06	69%	32%	52%
	Filter 3 Effluent	-	3.1	3.1	2.79	2.84	2.68	2.12	2.00	0.31	0.16	0.56	0.12	0.68	0.99	74%	34%	55%
Train 1 - Conventional w/Pre-chlorination @ 0.3 mg/L-Cl2	Filter 4 Effluent	0.3	3.1	3.4	3.02	3.03	3.03	2.76	2.64	0.38	0.00	0.27	0.12	0.39	0.77	68%	62%	65%
	Filter 5 Effluent	0.3	3.1	3.4	2.95	3.11	2.78	1.97	1.79	0.45	0.33	0.81	0.18	0.99	1.44	62%	4%	35%
	Filter 6 Effluent	0.3	3.1	3.4	2.96	3.01	2.91	2.72	2.60	0.44	0.10	0.19	0.12	0.31	0.75	63%	70%	66%

Note: all chlorine measurements reported in mg/L

Results and Discussion

Complete results of water quality analyses are provided in Appendix B.

Chlorine Demand and Decay

Chlorine residual concentrations throughout the test and associated demand and decay calculations are provided in Table 5 and presented in Figures 3a-d. Figures 3a and 3b display the free chlorine demand (green bars) and total chlorine decay (purple bars) as stacked bars, with Figure 3a including the total chlorine loss following ammonia addition and conversion to chloramines. Figure 3c displays the chlorine demand and decay across samples in more detail, distinguishing the first and second 7 days of the SDS period and including the portion of the free chlorine contact period that is pre-filtration. Figure 3d includes the 14-day total chlorine residual in the stacked bar, so the total bar represents the initial chlorine dose. In this figure, the dotted red line indicates the target chlorine residual at the end of the free chlorine contact period.

The following is a summary of the results and findings:

- Water collected from Lusted outlet on October 22 had initially been chlorinated using a dose of 3.7 mg/L, leaving Headworks with a free chlorine residual of about 3.0 mg/L. After about 320 minutes of contact time in the conduits and treatment at LHTF, the sample contained about 2.5 mg/L total chlorine. At the end of the 14-day SDS period, the residual total chlorine was 1.6 mg/L. Combining the CDD during the free chlorine contact period in Conduit 3 and during the 14-day incubation in the SDS bottles, the total CDD of the Lusted Outlet sample was 2.1 mg/L.
- Water collected that same day from the pilot raw inlet (same source as PWB's primary intake) was dosed with 3.4 mg/L chlorine and lost 0.7 mg/L during 60 minutes of free chlorine contact time and lost another 0.56 mg/L between secondary treatments and the end of the 14-day SDS period, a combined CDD of 1.2 mg/L. In comparison with the Lusted Outlet sample, the reduced CDD may be attributed to the reduced free chlorine contact time and the increased pH during the SDS period.
- In filtered samples, chlorine demand and decay over the free chlorine contact period and 14-day SDS period ranged from 0.75 to 1.44 mg/L. Compared with the Lusted outlet sample, the chlorine demand and decay was 52-56% lower in the pre-ozonated train filter effluents and 35-66% lower in the pre-chlorinated train filter effluents.
 - The target chlorine-to-ammonia ratio of 4.5 was not achieved in all treated samples. As evident in the pilot raw inlet, Filter 2, Filter 3, and Filter 5 samples, the higher dosing ratio resulted in some total chlorine loss during ammonia addition and lower than expected monochloramine concentrations. For these filtered samples, the total chlorine decay over the SDS period was greater than the other samples, a result which is highly influenced by the likely presence of dichloramine. The testing procedure will be modified for future SDS tests to ensure that target dosing ratio is met. While this was not the intent of the study, this finding does emphasize the importance of maintaining a chlorine-to-ammonia dosing ratio of less than 5:1.
 - Within the pre-chlorinated train, free chlorine demand following post-filter chlorine dosing was negligible (0.1 mg/L or less).
 - Within the ozonated train, GAC filter nos. 2 and 3 had lower free chlorine loss compared with the anthracite filter (no. 1).

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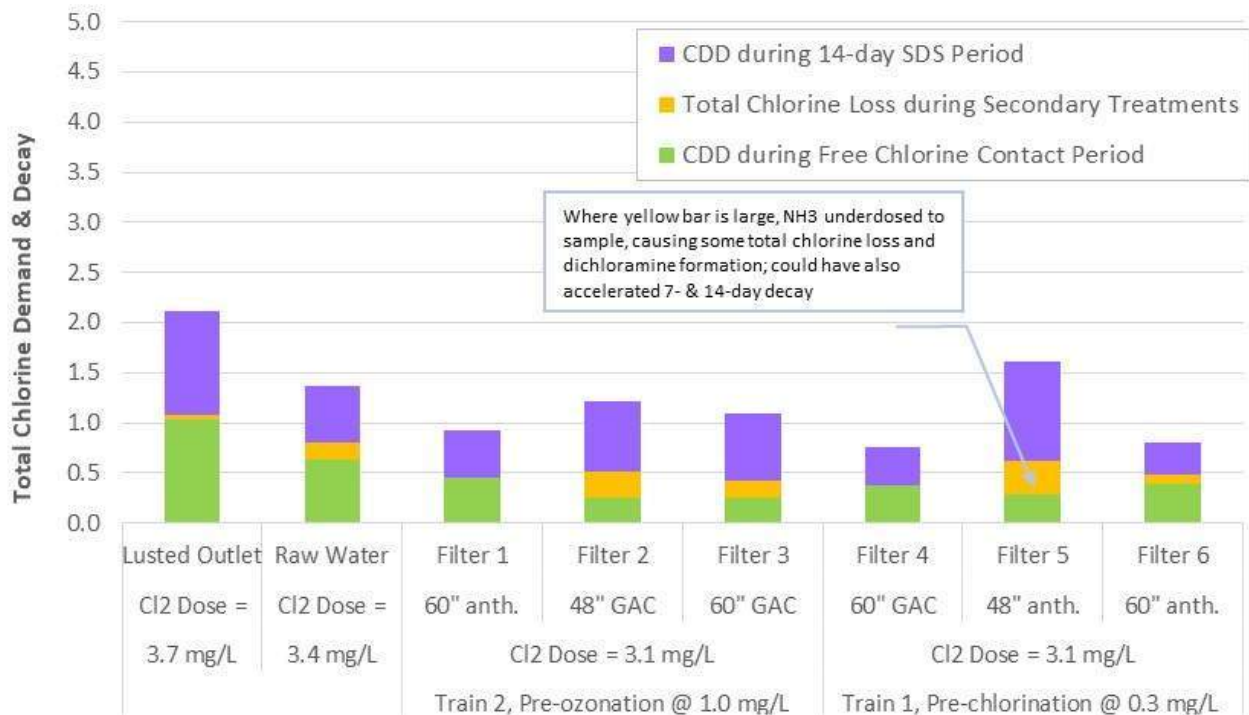


Figure 3a. Total Chlorine Demand & Decay over Free Chlorine Contact Period and 14-day SDS Period (including total chlorine loss during ammonia addition)

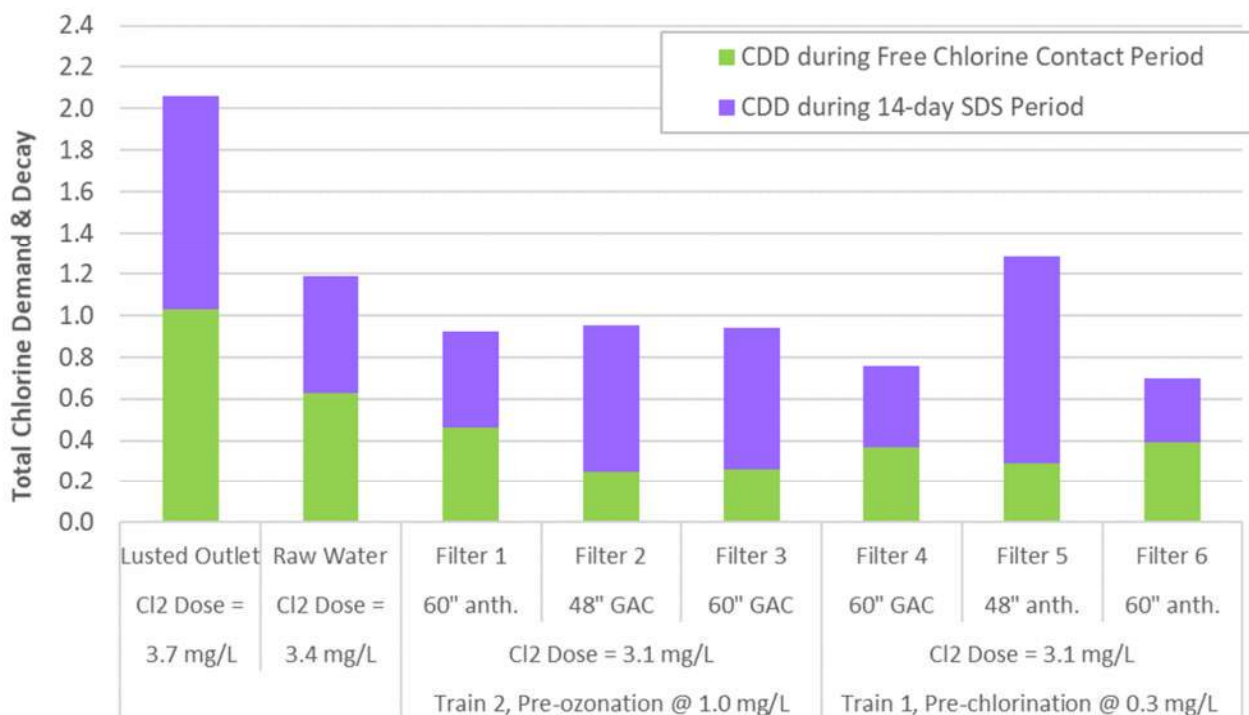


Figure 3b. Total Chlorine Demand and Decay over Free Chlorine Contact Period and 14-day SDS Period (excluding total chlorine loss during ammonia addition)

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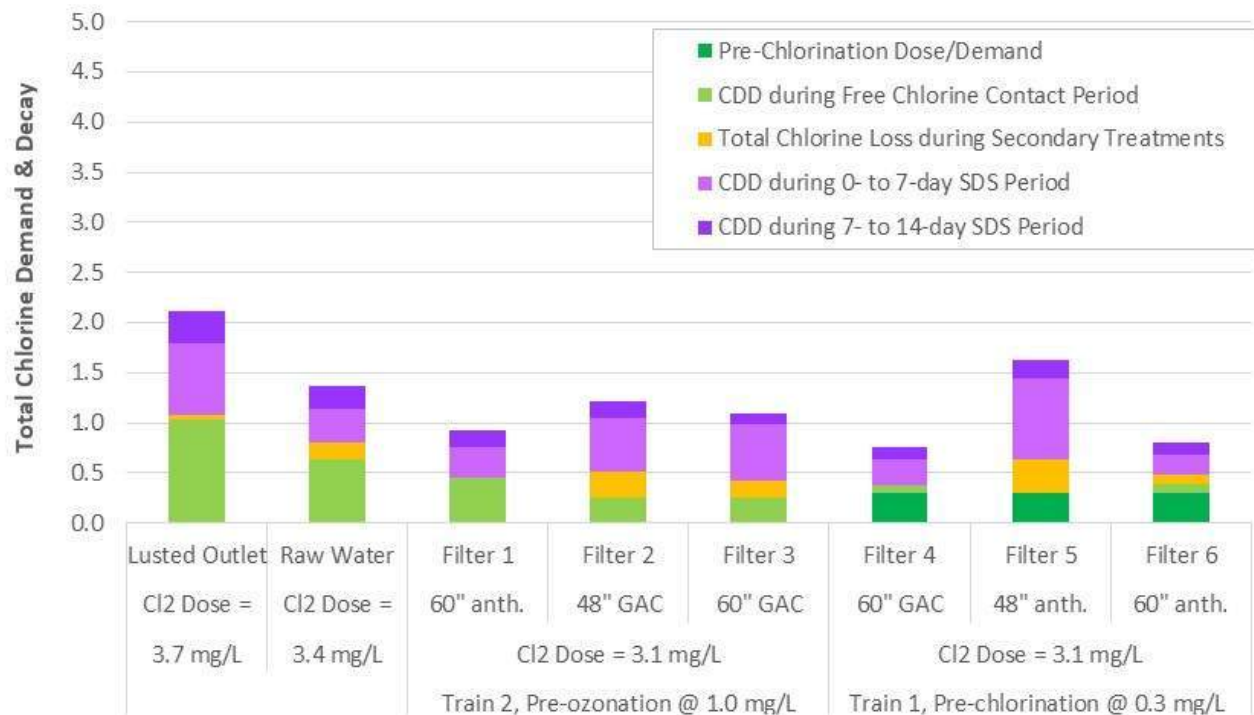


Figure 3c. Total Chlorine Demand and Decay over Free Chlorine Contact Period and 14-day SDS Period

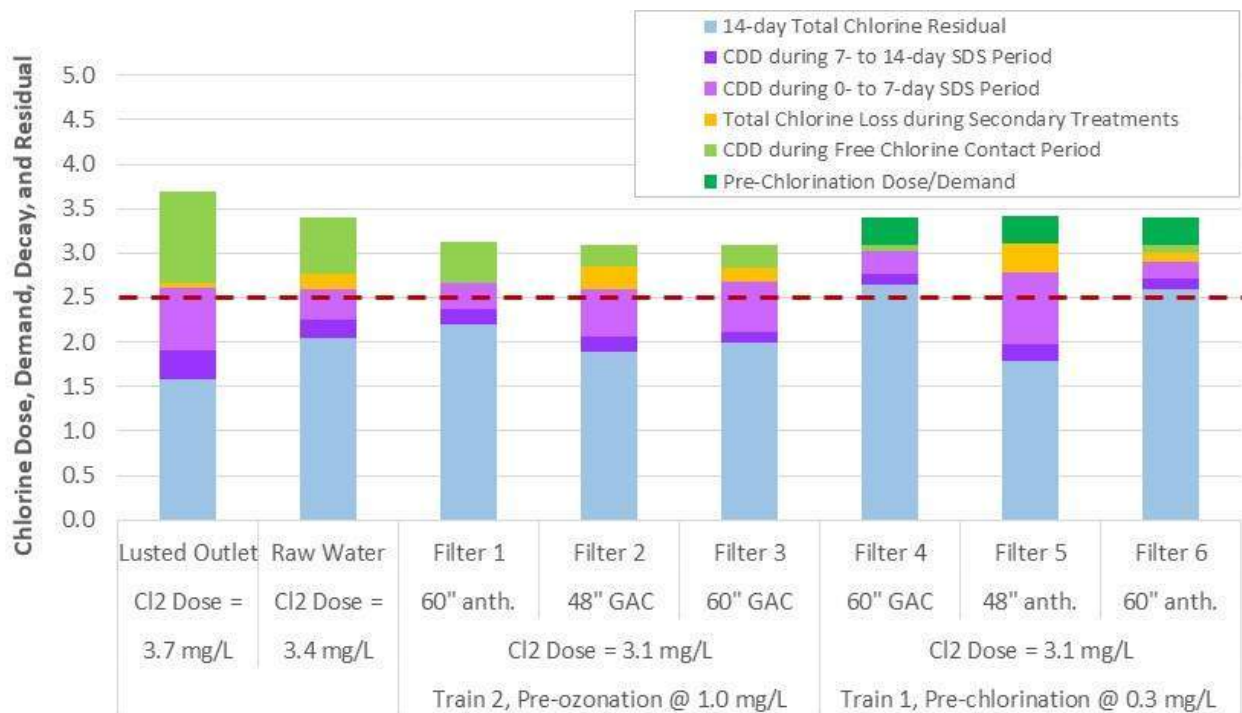
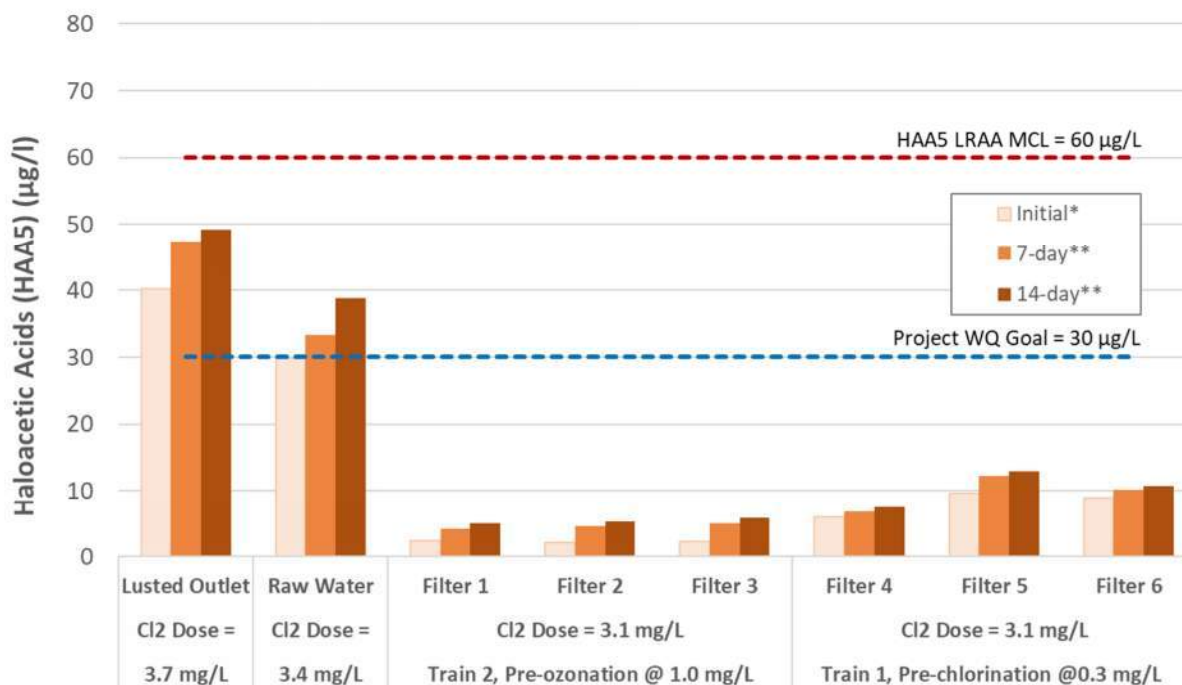


Figure 3d. Total Chlorine Dose, Demand, and Decay over Free Chlorine Contact Period and 14-day SDS Period

Disinfection Byproduct Formation

Results for THM's and HAA's are presented in Figures 4a-d. The following is a summary of findings related to disinfection byproduct formation:

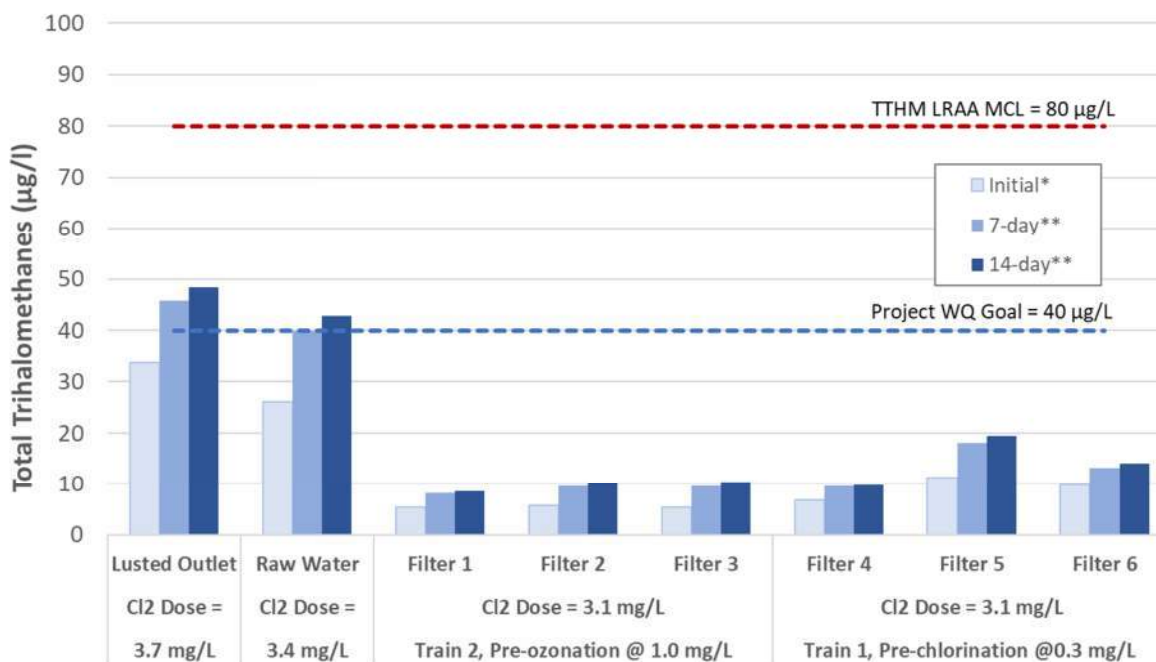
- Water collected from PWB's Lusted outlet initially contained a TTHM concentration of 33.8 µg/L and HAA5 concentration of 40.2 µg/L. Over the 14-day SDS period, these levels increased to 48.3 µg/L and 49.2 µg/L, respectively. While these levels are lower than the regulatory limits and within the normal range for this time of year, it is notable that they exceed the project's water quality goal for DBP's.
- Unfiltered pilot raw inlet water treated with the same disinfection and corrosion control targets as the filtered samples had significantly lower levels of both groups of DBPs compared with the Lusted outlet sample. Samples collected after all treatments were administered contained TTHM and HAA5 concentrations of 26.1 µg/L and 29.8 µg/L, respectively. After 14 days, the TTHM and HAA5 concentrations were 42.8 µg/L and 38.8 µg/L, respectively. The reductions in the initial formation of DBPs were expected due to the reduced free chlorine contact time. At the time of the test, water collected from Lusted Treatment Facility would have had about 320 minutes of contact with free chlorine. THM theoretical formation rates increase with increasing pH while HAA theoretical formation rates decrease with increasing pH. During the SDS period, the higher pH target (9.0) used for the pilot raw inlet sample may have resulted in an increased rate of THM formation.
- DBP levels were dramatically lower in the filtered effluent SDS samples compared with both Lusted Outlet and Pilot Raw Inlet SDS samples. At the end of the SDS period, filtered effluent samples had 60% to 82% lower TTHM levels and 75% to 92% lower HAA5 levels compared with the Lusted outlet sample.
- **Pre-ozonation vs. pre-chlorination:** While DBPs in all filtered effluent samples were well below the project goals, samples collected from the pre-ozonated train contained lower HAA and THM levels than the pre-chlorinated train. The difference may not be considered significant as DBP results from the filtered SDS samples were all less than 25% of the MCL's.
- **Anthracite vs. GAC:** Filters 2, 3, and 4 contain GAC caps while Filters 1, 5, and 6 contain anthracite caps. While GAC did not appear to provide a benefit in DBP reduction over anthracite in the pre-ozonated train filters, it appears to provide a benefit when using pre-chlorination as the single GAC filter (no. 4) had lower DBP levels than samples from Filter nos. 5 and 6. Since this test was conducted about 5 months into pilot plant operation and filter influent serving the pre-chlorinated train did not contain a chlorine residual, it is thought that biofiltration is the primary mechanism for removing DBP precursors in the GAC filters.
- **Effect of Free Chlorine Contact Time:** Samples collected from Filter 1 and Filter 6 effluents were tested for DBPs after 30- and 90-minutes free chlorine contact to bracket results from samples tested using 60-minutes of free chlorine contact time (Figures 4c-d). These samples were not treated further after the free chlorine contact time. Contact time within this range (30 to 90 minutes) did not appear to have a significant impact on DBP formation. It is notable that the addition of the secondary treatment chemicals (ammonium chloride, sodium bicarbonate, and sodium carbonate) increased the DBP levels of the 60-minute samples over the levels detected in the 90-minute samples that were not dosed with secondary treatment chemicals.



*Sample collected after free chlorine contact period and following addition of secondary treatments.

**Filter nos. 1 and 6 were sampled on days 6 and 13; all others were sampled on days 7 and 14

Figure 4a. Haloacetic Acid results at the beginning, middle, and end of the 14-day SDS period



*Sample collected after free chlorine contact period and following addition of secondary treatments.

**Filter nos. 1 and 6 were sampled on days 6 and 13; all others were sampled on days 7 and 14

Figure 4b. Total Trihalomethane results at the beginning, middle, and end of the 14-day SDS period

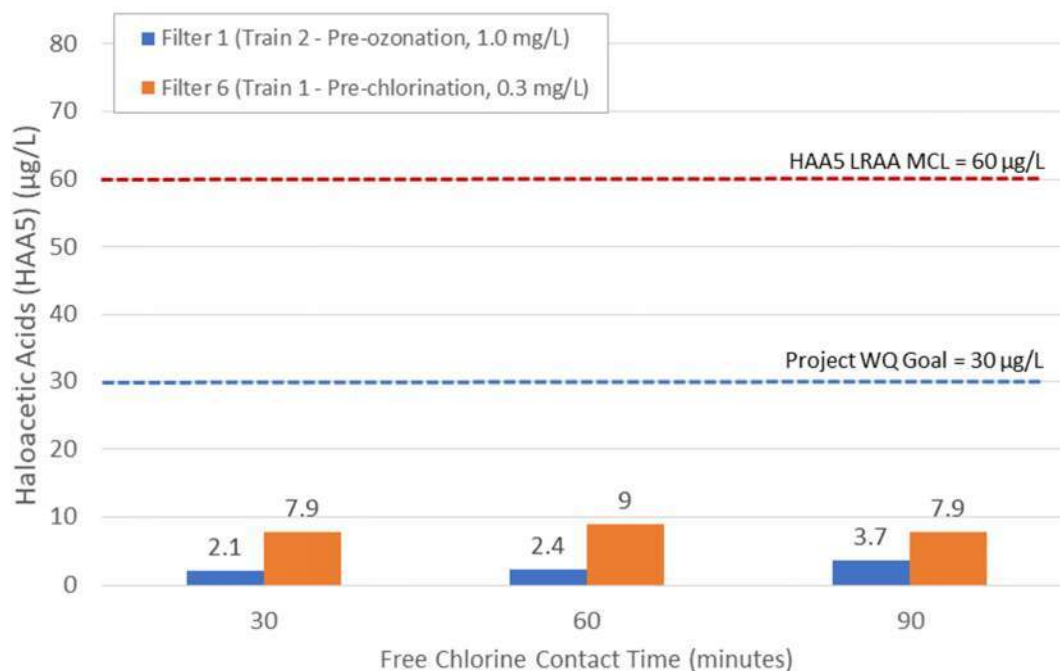


Figure 4c*. Haloacetic Acid results following 30, 60, and 90 minutes free chlorine contact

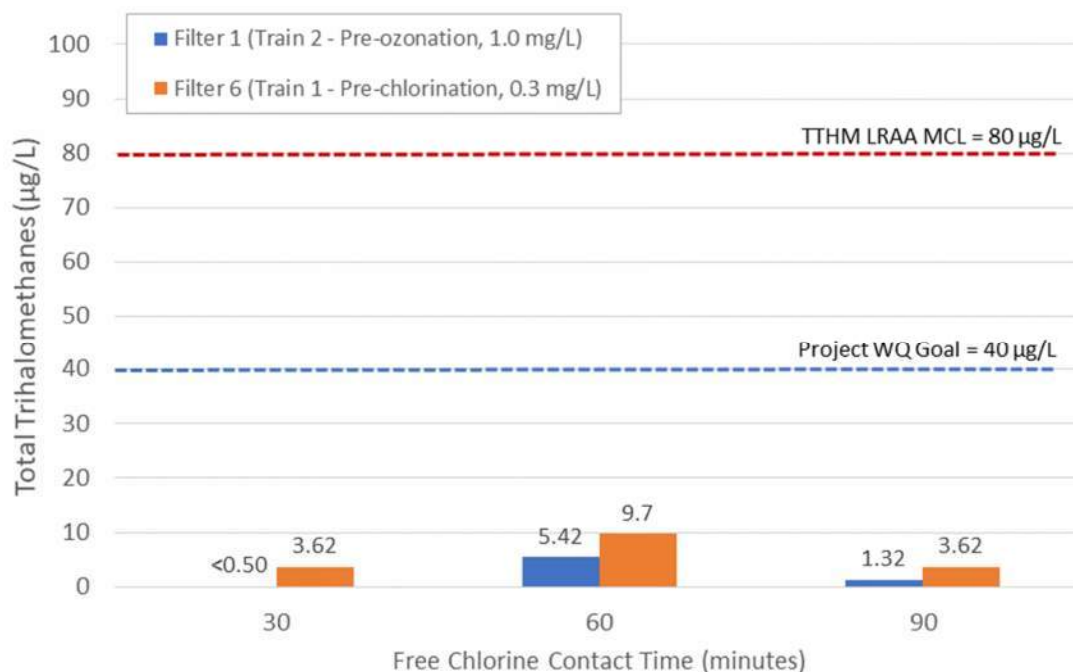


Figure 4d*. Total Trihalomethane results following 30, 60, and 90 minutes free chlorine contact

*Note: For 60-minute chlorine contact samples, samples were dosed with secondary treatments and then sampled about 10 minutes later for DBPs. For 30- and 90-minute samples, samples were collected for DBP analysis at the end of the free chlorine contact period and were not dosed with secondary treatments.

Conclusions

The results of the October 2019 SDS evaluation indicate that conventional treatment using the combination of pre-oxidation (with ozone or chlorine), coagulation, flocculation, sedimentation, and media filtration will be highly effective for controlling DBP's and chlorine demand and decay during disinfection and distribution of PWB water. The majority of the DBP reductions were found to be associated with coagulation and filtration treatment and the shorter free chlorine contact period that would be required for a filtration plant. The test results indicate that further reductions in DBP levels and chlorine demand and decay can be realized using pre-ozonation (over pre-chlorination) and GAC (over anthracite), though these additional reductions are not as significant.

SDS testing in water sampled from the pilot plant will be repeated in November, February, May, and August alongside PWB 2019-2020 distribution system DBP compliance sampling. In addition to testing for the suite of water quality parameters in the October test, the November test will include Flavor Profile Analysis.

Appendix A –

Simulated Distribution System Bench Testing Plan and Standard Operating Procedure

https://pwbpm.sharepoint.com/:w:/r/sites/PMDeIv2/_layouts/15/Doc.aspx?sourcedoc=%7BE73A4519-A5F2-415D-AF3C-32A88BB449BA%7D&file=220-1_SOP%20-%20SDS%20and%20FPA%20Testing%20-%20rev3%2020191017.docx&action=default&mobileredirect=true

Portland Water Bureau

Water Quality



Appendix B –

October 2019 SDS Test Water Quality Data

Portland Water Bureau Water Quality



Sample Type	LOCCODE	Date Collected	LOCDESCR	Temp. (deg. C)	pH	Alkalinity (mg/L-CaCO3)	TURB-WQ	Apparent Color (CU)	True Color (CU)	UV254 (cm ⁻¹)	TOC (mg/L)	DOC (mg/L)	Total Chlorine (mg/L)	Free Chlorine (mg/L)	Mono-chloramine (mg/L)	Free Ammonia (mg/L-N)	Total Ammonia (mg/L-N)	HAA-552-3 (ug/L)	THM-524-2 (ug/L)
Initial Water	FILTP-RI-PLT	10/22/19 10:20	Raw Inlet Pilot	15	7.48	11.1	0.48	17	10	0.059	1.4	1.3							
	FILTP-OZ-155	10/22/19 13:46	Pre-Oxidant Contactor Outlet Train 1				0.53	15	7	0.053	1.4	1.4							
	FILTP-OZ-255	10/22/19 14:00	Pre-Oxidant Contactor Outlet Train 2				0.45	9	0	0.029	1.5	1.5							
	FILTP-SW-T1	10/22/19 13:10	Settled Water Floc/Sed 1000				1.08	14	0	0.039	1.1	0.59							
	FILTP-SW-T2	10/22/19 13:32	Settled Water Floc/Sed 2000				1.36	13	0	0.033	1.4	0.77							
	FILTP-FE-2	10/22/19 11:05	Filtered Effluent 2	15.8	6.9	10	0.19	0		0.006	0.59	0.57							
	FILTP-FE-3	10/22/19 11:55	Filtered Effluent 3	14.8	6.97	9.6	0.18	0		0.007	0.62	0.59							
	FILTP-FE-4	10/22/19 14:05	Filtered Effluent 4	15.3	6.92	9	0.14	0		0.007	0.44	0.43							
	FILTP-FE-5	10/22/19 13:30	Filtered Effluent 5	15	6.9	8.9	0.07	0		0.01	0.57	0.62							
	FILTP-RI-PLT	10/23/19 10:48	Raw Inlet Pilot		7.08		0.49	16	8	0.057	1.4	1.4							
	FILTP-OZ-155	10/23/19 11:49	Pre-Oxidant Contactor Outlet Train 1		6.89		0.43	14	7	0.054	1.4	1.6							
	FILTP-OZ-255	10/23/19 12:17	Pre-Oxidant Contactor Outlet Train 2		6.79		0.46	8	1	0.034	1.5	1.8							
	FILTP-SW-T1	10/23/19 11:14	Settled Water Floc/Sed 1000		6.74		0.93	12	0	0.034	1	0.62							
	FILTP-SW-T2	10/23/19 11:36	Settled Water Floc/Sed 2000		6.83		1.34	12	0	0.034	1.3	0.76							
	FILTP-FE-1	10/23/19 10:47	Filtered Effluent 1	14	6.59	8.8	0.2755	0		0.008	0.74								
	FILTP-FE-6	10/23/19 12:40	Filtered Effluent 6	FE	6.64	8.6	0.33	-1		0.007	0.55								
	EXPSAMP	10/23/19 10:30	DI Water	FE	6.05	2.1	0.17	-1		-0.001									
Disinfected Water	EXPSAMP	10/22/19 11:29	Raw Inlet Pilot Disinfected Water	17	FE	FE		14		0.052			2.77	2.72					
	EXPSAMP	10/23/19 12:20	Filtered Effluent 1 Disinfected Water	14.8	6.93	11.1		-1		0.008			2.64	2.59					
	EXPSAMP	10/22/19 12:19	Filtered Effluent 2 Disinfected Water	14.2	7.06	10.8		0		0.012			2.85	2.74					
	EXPSAMP	10/22/19 13:06	Filtered Effluent 3 Disinfected Water	15.6	7.07	13.7		-1		0.007			2.84	2.79					
	EXPSAMP	10/22/19 15:15	Filtered Effluent 4 Disinfected Water	14.8	7.05	11.1		-1		0.006			3.03	3.02					
	EXPSAMP	10/22/19 14:36	Filtered Effluent 5 Disinfected Water	14.9	7.08	14.9		0		0.012			3.11	2.95					
	EXPSAMP	10/23/19 14:06	Filtered Effluent 6 Disinfected Water	14.7	7.1	10.9		-1		0.007			3.01	2.96					
	EXPSAMP	10/23/19 11:58	Filtered Effluent 1 DW 30 min contact	14.5	6.99	11.2		-1		0.01			2.73	2.69				2.1	<0.50
	EXPSAMP	10/23/19 12:48	Filtered Effluent 1 DW 90 min contact	13.7	7.07	11.3		0		0.008			2.64	2.58				3.7	1.32
	EXPSAMP	10/23/19 14:40	Filtered Effluent 6 DW 30 min contact	14.7	7.03	10.8		-1					2.99	2.92				7.9	3.62
	EXPSAMP	10/23/19 14:28	Filtered Effluent 6 DW 90 min contact	15	7.05	10.9		-1		0.007			2.98	2.89				9.4	4.65
	EXPSAMP	10/23/19 12:41	DI Water Disinfected Water	13.2	7.41	3		-1		0.001			2.52	2.52					
"T0" SDS Samples (collected 10 mins after secondary treatments added)	EXPSAMP	10/22/19 11:46	Raw Inlet Pilot T0	15	8.4	FE		13		0.069	1.4		2.6		2.47	<0.05	0.47	29.8	26.1
	EXPSAMP	10/23/19 12:34	Filtered Effluent 1 T0	14.2	8.77	34.8		-1		0.021	0.79		2.66		2.51	0.09	0.59	2.4	5.42
	EXPSAMP	10/22/19 12:29	Filtered Effluent 2 T0	14.3	8.55	34.8		-1		0.018			2.59		2.5	<0.05	0.5	2.1	5.66
	EXPSAMP	10/22/19 13:18	Filtered Effluent 3 T0	14.5	8.54	34.5		1		0.02	0.64		2.68		2.53	<0.05	0.47	2.2	5.38
	EXPSAMP	10/22/19 15:25	Filtered Effluent 4 T0	15.3	8.64	34.3		-1		0.02	0.46		3.03		2.85	<0.05	0.57	5.9	6.73
	EXPSAMP	10/22/19 14:46	Filtered Effluent 5 T0	14.7	8.77	34.6		1		0.019	0.59		2.78		2.45	<0.05	0.45	9.6	11.3
	EXPSAMP	10/23/19 14:11	Filtered Effluent 6 T0	14.8	8.6	34.4		-1		0.02	0.55		2.91		2.75	0.03	0.58	9	9.7
	TRLHC3LO	10/22/19 8:51	C3LO: CON3 LUSTED OUT -LUSTED	15.3	7.84	13.8		10		0.055	1.3		2.62		2.43	<0.05	0.46	40.2	33.8
	EXPSAMP	10/23/19 12:58	DI Water T0	12.5	9.12	31.8		-1		0.011	<0.30		2.46		2.37	<0.02	0.44		

Portland Water Bureau
Water Quality



Sample Type	LOCCODE	Date Collected	LOCDESCR	Temp. (deg. C)	pH	Alkalinity (mg/L-CaCO3)	TURB-WQ	Apparent Color (CU)	True Color (CU)	UV254 (cm ⁻¹)	TOC (mg/L)	DOC (mg/L)	Total Chlorine (mg/L)	Free Chlorine (mg/L)	Mono-chloramine (mg/L)	Free Ammonia (mg/L-N)	Total Ammonia (mg/L-N)	HAA-552-3 (ug/L)	THM-524-2 (ug/L)
"T7" SDS Samples (collected 6-7 days after secondary treatments added)	EXPSAMP	10/29/19 11:38	Raw Inlet Pilot T7	13.6	9.19	36		13		0.059			2.26		2.19	0.04	0.48	33.3	39.9
	EXPSAMP	10/29/19 12:03	Filtered Effluent 1 T7	8.5	8.85	34		1		0.02			2.37		2.33	0.11	0.57	4.2	8.13
	EXPSAMP	10/29/19 12:20	Filtered Effluent 2 T7	9	8.71	34		1		0.016			2.06		2.02	0.01	0.41	4.6	9.53
	EXPSAMP	10/29/19 12:39	Filtered Effluent 3 T7	9.6	8.76	34		1		0.021			2.12		2.09	0.03	0.44	5	9.54
	EXPSAMP	10/29/19 12:57	Filtered Effluent 4 T7	8.6	9	34		1		0.018			2.76		2.73	0.05	0.59	6.8	9.5
	EXPSAMP	10/29/19 14:11	Filtered Effluent 5 T7	9.8	8.79	34		1		0.016			1.97		1.97	0.01	0.4	12.2	18
	EXPSAMP	10/29/19 14:30	Filtered Effluent 6 T7	8	8.98	33		0		0.019			2.72		2.73	0.06	0.59	10.2	13.2
	EXPSAMP	10/29/19 14:41	Conduit 3 Lusted Out (Lusted) T7	9.6	7.8	13		11		0.05			1.91		1.83	0.06	0.42	47.4	45.8
	EXPSAMP	10/29/19 14:54	DI Water T7	8.3	9.37	31		0		0.011			2.06		2.03	0.04	0.44		
"T14" SDS Samples (collected 13-14 days after secondary treatments added)	EXPSAMP	11/5/19 11:03	Raw Inlet Pilot T14	11.1	9.19	36		13		0.062			2.04		2.01	0.08	0.48	38.8	42.8
	EXPSAMP	11/5/19 11:23	Filtered Effluent 1 T14	9.9	8.84	33		1		0.02			2.2		2.26	0.12	0.56	5	8.46
	EXPSAMP	11/5/19 11:39	Filtered Effluent 2 T14	10.6	8.56	35		1		0.02			1.89		1.94	<0.05	0.41	5.3	10
	EXPSAMP	11/5/19 11:54	Filtered Effluent 3 T14	10.7	8.46	34		1		0.019			2		1.94	<0.05	0.41	5.8	10.4
	EXPSAMP	11/5/19 12:09	Filtered Effluent 4 T14	10.3	8.97	34		1		0.031			2.64		2.66	<0.05	0.55	7.4	9.66
	EXPSAMP	11/5/19 12:22	Filtered Effluent 5 T14	10.2	8.86	34		1		0.019			1.79		1.82	<0.05	0.39	13	19.5
	EXPSAMP	11/5/19 12:34	Filtered Effluent 6 T14	9.8	8.97	34		1		0.021			2.6		2.61	<0.05	0.54	10.8	14.1
	EXPSAMP	11/5/19 14:17	Conduit 3 Lusted Out (Lusted) T14	11.8	7.79	13		11		0.049			1.59		1.58	0.1	0.41	49.2	48.3
	EXPSAMP	11/5/19 14:29	DI Water T14	10.3	9.32	31		1		0.012			1.7		1.72	0.07	0.41		